AN ANALYSIS OF PROGRESSIVE ADDITION SPECTACLE LENS DESIGN BY THE USE OF INTERFEROMETRY

EVANGELOS PATERAS

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October 2005

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Thesis Summary

Progressive addition spectacle lenses (PALs) have now become the method of choice for many presbyopic individuals to alleviate the visual problems of middle-age. Such lenses are difficult to assess and characterise because of their lack of discrete geographical locators of their key features.

A review of the literature (mostly patents) describing the different designs of these lenses indicates the range of approaches to solving the visual problem of presbyopia. However, very little is published about the comparative optical performance of these lenses.

A method is described here based on interferometry for the assessment of PALs, with a comparison of measurements made on an automatic focimeter. The relative merits of these techniques are discussed. Although the measurements are comparable, it is considered that the interferometry method is more readily automated, and would be ultimately capable of producing a more rapid result.

Key words

Progressive addition lenses, varifocal, optical quality, interferometry

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Chapter 1

Progressive addition lenses

Introduction

Progressive addition lenses (PALs) are for the last twenty-five years the major solution for far, intermediate and near clear vision for presbyopic patients. Through these years a lot of changes have been made in the design of such lenses while all the effort of the manufacturers of such lenses is targeted to satisfy the needs of all the presbyopic population.

These lenses are very complicated in their design so measuring, testing and evaluating the performance of such lenses is essential for the optical market. As much as we know about these special lenses is a necessity in order to provide the optical market and the wearers of such lenses all the information needed for their best use.

This chapter deals with what progressive addition lenses are, their major design types, how these lenses are assessed for their performance using wearer trials, and the way that the optical community describes their optical properties.

Progressive addition lenses

Presbyopes need at least two different corrections, one for distance viewing and one for near. In the 19th century, the invention of the bifocal lens aided presbyopic wearers, because it allowed two different prescriptions to be present in the same frame. The invention of the bifocal is usually attributed to Benjamin Franklin (split type), but some bifocals may have existed previously *(Levene, 1977)*.

Over the years, the method of manufacture, size and location of the segments, and number of segments have been modified to produce today's designs. The main problem for wearers of bifocals is the visible line dividing the near and distance sections, and the image jump presented due to the abrupt change of power at the dividing line, either by the sudden change of curvature (solid bifocals) or the change of the refractive index of the near segment (fused bifocals). To overcome this and in order to provide clear vision for intermediate distances, progressive addition lens (PAL) were introduced. PALs have no visible lines, as there are no discontinuities in power on the surface of the lens. The power varies continuously through the intermediate or progressive zone between a stable distance zone and a near zone. This is normally achieved by continuously decreasing the radius of curvature on the front surface.

Conventional progressive addition lenses are one-piece lenses that vary gradually in surface curvature from a minimum value in the upper, distance section, to a maximum value in the lower, near section. This results in a smooth, continuous increase in surface power that provides the necessary near addition, without any visible lines of demarcation or abrupt disturbances of vision. Figure 1.1., below shows the gradual change in curvature and surface power towards the lower, near section of the lens.

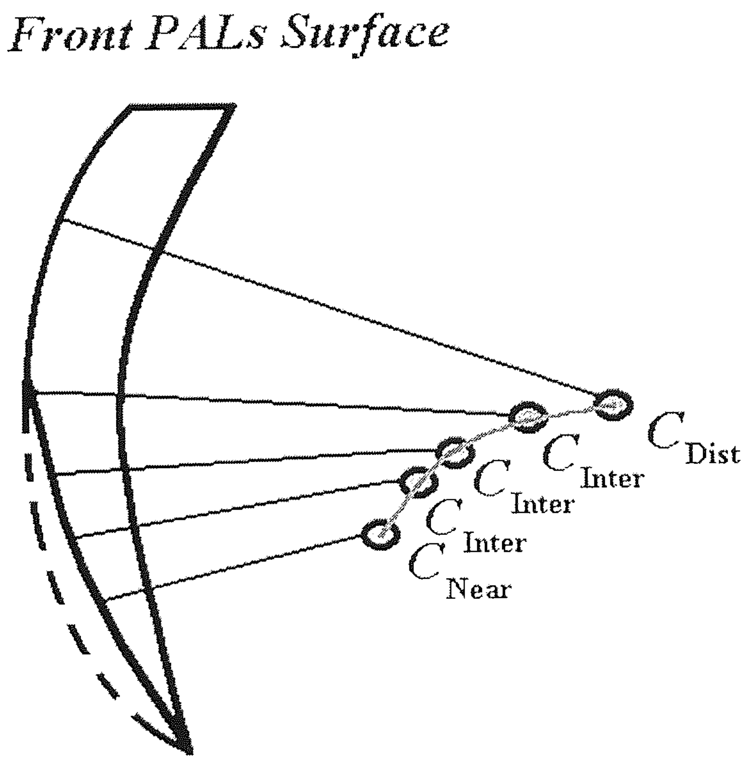


Figure 1.1. *Cross-sectional representation of a progressive lens surface. The shorter radius of curvature in the near portion at point C_{Near} provides a stronger surface power than the longer radius of the distance portion at C_{Dist}. C_{Inter} are radii of curvature representing the progression corridor of the lens surface.*

A conventional, general-purpose progressive lens will have three distinct zones of vision:

1. Distance zone. Located in the upper section of the lens, which provides the necessary distance correction.
2. Near zone. Located in the lower section of the lens, which provides the required near correction.
3. Intermediate zone. Located in the middle section of the lens. In this section of the lens a "corridor" connects these above two zones, progressively increasing the plus power from the distance to near zone.

The two basic extreme lens designs of PALs are:

A) ***Hard lens design***. Employs a short, rapid power progression. Due to such a progression of power, a large amount of aberration concentrates in the lens periphery. The short, rapid power progression of the hard PAL design, by concentrating aberration in the lens periphery, temporally and nasally, leaves large areas of the lens totally free of distortion. The advantage of such a design is that large distance and near vision zones are created that are totally free of distortion providing an excellent distance and near vision when the wearer looks through the central part of the lens. The very high concentrations of aberration in the periphery of the lens creates blurred vision and distortion, while the intermediate vision zone is very narrow.

B) ***Soft lens design***. Such design uses a long, gradual progression, spreading smaller amounts of aberration more evenly throughout the lens surface. Because there are no heavy concentrations of aberration in the lens periphery, visual acuity is less distorted, while a much wider intermediate zone of vision is presented. Such designs are successful with new presbyopes (add power less than 1.50 D), while the narrow distance and near vision zones may seriously reduce visual comfort for mature presbyopes.

Progressive lenses have been around since 1907, firstly introduced by Aves (*Sullivan & Fowler, 1988)*. Although early progressive lenses were rather hard in their design, they have consistently improved in both performance and sales over the past few decades. The Varilux lens, launched in Europe in 1959, was the first commercial PAL, while the first PAL launched in the US was the Omnifocal lens in 1961.

Several methods were used for evaluating the optics of progressive addition lenses. The most common and convenient method of describing progressive lens surfaces is the contour map. Contour maps are similar to topographical maps, and use lines where all the points between each line correspond to equal surface power. Each contour line represents an increasing level of power at a given interval, usually of 0.50 D step. Either a mean power contour plot or a power profile plot can describe the gradual power increase. Both quantify the change in power, either by mapping the zones of increasing power, or by plotting it as the power changes along the progressive corridor (or umbilical line). The lens surface depicted in Figure 1.2., below, has a +2.00 D add power.

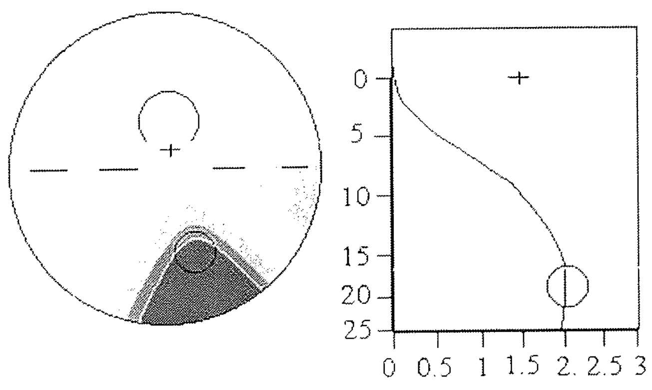


Figure 1.2. *A mean power contour plot is similar to a topographical map. It shows by changing colour how the mean power is spread over the lens surface. A power profile plot shows how the power progress from the top to the bottom of the lens surface at the progression corridor plane.*

The mean power contour plot shows the gradual increase in plus power towards the near section of the lens. Each contour level represents 0.50 D step of additional plus power. Contour plots, although a useful tool for analyzing and comparing the optics of a progressive addition lens, are simply mathematical models of the lens surface. Although they may be indicative of lens performance, they are not enough to predict patient acceptance.

Although, PALs are obviously a very good solution for presbyopes, their design comes at the cost of increased peripheral astigmatism and distortion. It is impossible to create a progressive surface without optical errors in the periphery of the lens *(Fannin & Grosvenor, 1996)*. The typical layout of a PAL is demonstrated in Figure 1.3.

Figure 1.3. shows the levels of surface astigmatism in a PAL. Each change in shading is equivalent to 0.5D of astigmatism with the darkest area indicating between 1.5 and 2D.

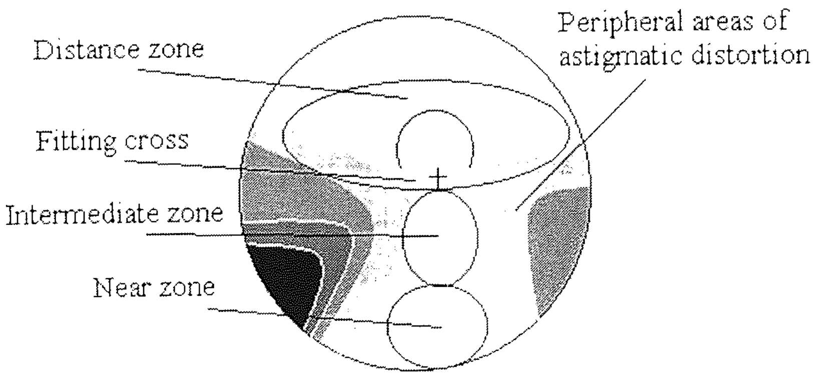


Figure 1.3. *Typical type of a progressive addition lens. The contours show how astigmatic power changes through the lens surface, from the centre of the lens to the periphery, while the clear distance, intermediate and near vision zones are free of astigmatism.*

Market trends

As mentioned above it is impossible to design a progressive surface without having peripheral astigmatism or distortion. Although PALs have this drawback, they have been on the market for more than 40 years. During this time, new milling technology, progress in design software and the mathematics have enabled PAL manufacturers to reduce this drawback (the peripheral distortion) to its theoretical limits. Designers of PALs have to balance between a large numbers of design features. The existence of infinite design combinations, the variety of human tasks for which the lenses will be used and advances in understanding the human visual system, cannot produce only one single right design for all wearers at all situations. Changing working and leisure activities may also render previously acceptable designs inappropriate.

By designing progressive addition lenses we are able to alter zone sizes, reduce or increase the progressive corridor and move the locations of the distortions and unwanted astigmatism at the edges of the lens. However, these are not independent variables. Changing the size of one zone affects the size of the others and alters the levels of the distortions. For example, some wearers complain that they have to tilt their head back too far in order to be able to read text at close range. One solution is to shorten the length of the progression zone, known as the corridor length. This might enable the wearer to read without tilting his head back as far, but it will raise the levels of the peripheral unwanted astigmatism and blur. In some cases the wearer might having difficulty in moving the head from side to side in order to read his newspaper because the field of the near zone is too small. Unfortunately, by making the near reading area wider we must shorten the corridor and an increase of the peripheral distortion will be present. The task of finding the right balance is a difficult one and this is the reason for the existence of so many designs nowadays.

Examples of different designsused so far are shown in Figure 1.4. Surface astigmatism and surface mean power, are shown for three different PAL designs: a *hard* design lens, a *soft* design lens and an *ultra-soft* design.

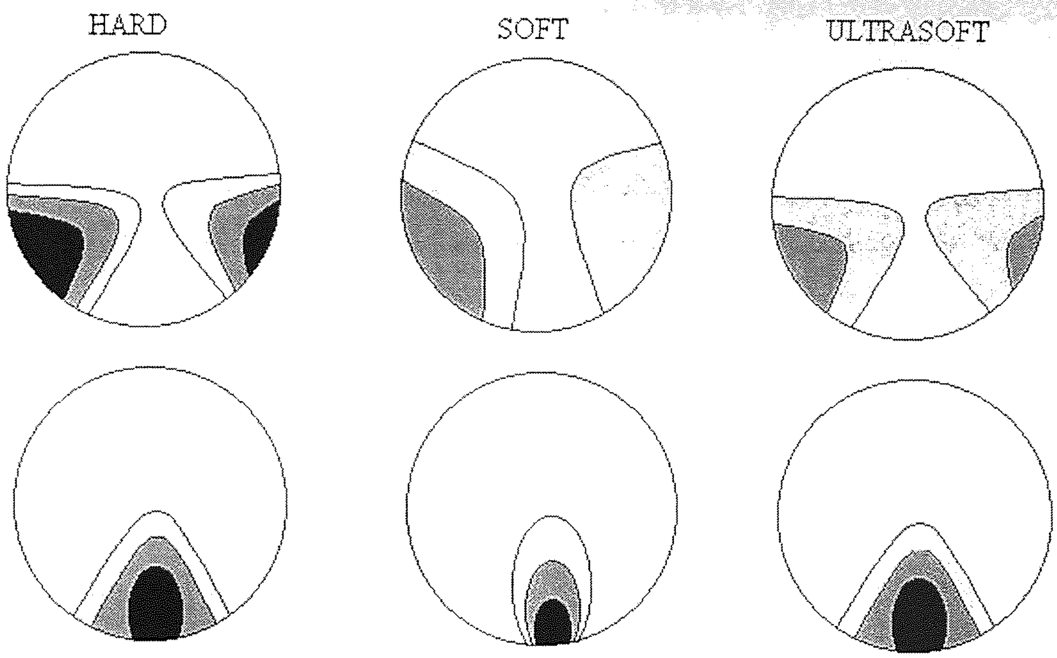


Figure 1.4. *Surface astigmatism and surface mean power, are shown for three different PAL designs: a hard design lens, a soft design lens and an ultra-soft design. The two extremes are the hard and the soft lens design. The ultra-soft is in the middle where the advantages of the two previous designs are used to form a better lens design, where a large distant and near vision zone is presented with low astigmatism in the periphery of the lens.*

Basically we must have in mind that in order to minimize peripheral distortion the changes in curvature of the lens must be distributed over a larger area on the lens, but by doing so, the lens will present smaller areas of clear vision. This is a characteristic of the *soft* design. Also we must try to minimize the peak of unwanted astigmatism presented in the periphery of the lens surface on both sides of the progression corridor and how quickly this astigmatism accelerates starting from the progression corridor.

We must also keep in mind that the frame selection affects the blur and distortion wearers see through the lens. The smaller the frame is, the more of the peripheral blur and distortion that will be edged off the lens. The problem with smaller frames is that if the frame gets too small, the full addition power of the lens will not be incorporated. So, patients should select small frames that give them adequate vertical eye movement in order to have clear near vision. Another important variable is that the design must satisfy the binocular vision balance. The lenses must be design asymmetric (different design for right and left eye) in order the wearer to encounter the same vision with both eyes.

Wearer Trials

Manufacturers perform wearer trials, in order to assess how wearers accept a new design, that, and to see if it will have a potential success in the marketplace.. In such trials, wearers use the new lenses for a certain period and their performance is rated. Wearers have to answer three major areas of question in such trials: How easily acceptable are the new lenses and how they perform and if there are older or other designs which they prefer. So, in acceptance trials, wearers are given a PAL for a certain period and are later asked if they would like to keep wearing the new lens or return to what they were previously had. In preference trials, wearers are given two different new lenses and are asked which one they prefer. More detailed information about acceptance and preference trials is given below.

Acceptance wearer Trials

In an acceptance trial success is rated on whether the wearer is still wearing the lens being offered at the end of the trial, and whether he is satisfied by its performance. The measure used to gauge satisfaction varies from trial to trial but generally, satisfaction is rated on a scale from 1 to 5 or 10 e.g. (1 being the worst, 5 the best). Examples of PAL acceptance trials are those performed by *Schwartz and Schwartz (1967), Wittenberg (1978), Chapman (1978), Augsburger et al. (1984), Sullivan and Fowler (1989), Cho et al. (1991), Gresset (1991), Boroyan et al. (1995), Young and Borish (1994) and Kris (1999)*. The average level of acceptance in these trials is about 92.50 % and varies from 86 to 99 %. Satisfaction score is a bit lower, ranging between 72 and 92 %, averaging 82 %.

Also by looking at the results of these trials we can conclude that: a) previous PAL wearers (*Gresset, 1991)*, b) those with a high distance prescription and lower add power (*Wittenberg, 1978)*,c) those for whom the trial lens was their first multifocal prescription (*Schwartz, Schwartz Jr., 1967)* appeared more likely to succeed with a new PAL.

Young and Borish (*1994)* and *Murphy, (1999)* studies showed that the success of a PAL design is depending on the proper fitting that the optician does. Proper fitting and patient education are sometimes even more important than the actual design of the lens.

Preference of PAL's vs. Bifocals

In such trials *(Boroyan, et al., 1995),* PALs were favored over bifocal corrections. Through the years the preference of PALs increase and although in the earliest studies, preference was only 52 % for PALs over bifocals, in the most recent studies preferences of PAL's goes over 90 %. According to the wearers' answers they prefer PALs because they are better cosmetically, there is no dividing line, they present better intermediate vision and no image jump. The wearers of bifocals select these lenses because they present a wider near field of view, and they do not have side distortion.

Preference between PALs

When wearer trial studies take place where one PAL is compared to other PAL design *(Brookman, et al, 1988),* unfortunately the design of the company who sponsored the trial was found to be better than the one compared. This cannot considered an independent study so it cannot consider objective. There is one study *(Fowler, et al., 1994)* that did not name the lenses given to wearers but described their qualities and design. This study showed that the preference stated for both PAL's examined were very close, 52 to 48 %. This indicates that different designs can be equally preferred and wearers can adapt nearly the same.

In the *Wittenberg et al. (1989)* study, comparing different designs between different groups of wearers showed that male subjects seemed to prefer the designs with lower grading of astigmatism compared to females. Lenses with low astigmatic grading are called *"soft"* designs, while lenses with high grading are called *"hard"* designs.

Adaptation

A major objective for PALs designs is adaptation. A number of presbyopes, small in number, fail to adapt to their lenses. So an important target of PAL manufacturers is to minimize the number of wearers who do not adapt in order to maximize the successful wearer group.

Adaptation is the key and is related to many variables. "Swim" and image distortion in the periphery of a PAL are important variables. "Swim" can cause dizziness, headaches and nausea and is responsible for a percentage of the failure wearers.

There are other variables that relate to adaptation as well. The wearer must adapt to the ergonomics of the lens. Every lens design present different zone sizes and locations, and the wearer must learn how to position their head and eyes in order to use properly their lenses and see clearly at all distances. Another problem is static distortion, where straight lines appear to be bent, which some wearers find quite disturbing. Also binocular vision is an issue. Wearers must adapt to complex prism fields (*Tuan and Jones, (1997)* and some wearers find it difficult to use their PAL's binocularly. One wearer also may be able to switch between several different lens designs easily while others may have great difficulty any time they change anything about their lenses.

Another important factor influencing adaptation is that some wearers might fail to adapt due to fitting failure. If in an optical practice failure rate is higher than an acceptable level over a period of about 100 wearers then the practice's fitting, especially PD measurements and fitting height, should be checked. Also patient education should be looked after, and finally the choice of the proposed lens design should be considered.

Analyzing PALs

PAL manufacturers and designers argue on how it is best to analyze lenses. For example how they should measure the corridor length and width. Some analyze this based on surface quantities while others on optical quantities.

A common practice for demonstrating astigmatism and mean spherical power is by contour plots. Commonly these plots map the front surface characteristics of the lenses, where the progression exists, or sometimes the lenses are mapped by using focimeter readings. Neither of these techniques gives an accurate picture of how the lens will perform when worn *(Bourdoncle, et al., 1992)*. This is true because someone must take into consideration the distance prescription and the way the lenses are worn in front of the eye.

The latest proposed practice in assessing Pal's is to use plots based on a ray trace of the complete lens in front of a model eye or by mapping the optical quantities based on eye point performance. Accurate ray tracing has become a possible solution with the help of fast modern computers and related software which allows a lens designer to determine the overall performance of a potential lens design as it if was in front of a wearers eye although it only exists as a design file on a computer. Once the PAL's surface is stored in such a manner that a suitable ray-tracing program can be use, an unlimited number of analyses of that surface can be performed. Ray traced analysis or eye point mapping offer a marked improvement over older methods of analysis and helps the design to alter variables in order to optimise performance according to use.

Designers and manufacturers are trying to improve the design of PALs over the years in order to satisfy more customers. That is why new lenses are regularly launched in the market. Progressive addition lenses for the time being represent the best solution for correcting presbyopia. Their sale is about 25 % of the lenses purchased, while, the trend is to rise as more presbyopic patients accept them in the future *(Pointer, 1998)*.

The future of PALs looks very promising. Although they present problems and limitations, PALs are the best choice for a large share of the presbyopic patients. In order to understand more about PALs, a patent review is necessary.

Summary

At present progressive addition lenses (PALs) represent the major current commercial solution in multifocal corrections for presbyopia. They represent 25 % of the lenses purchased, and 70 % of the solutions used for correcting presbyopia (among contact lenses, surgery etc.) and this is likely to rise as they become more accepted by the presbyopic population. Although their market launch started over forty years ago, new and improved PALs are consistently released.

The improvement in PAL design over the years is due to the greater understanding of progressive surfaces, better and more detailed manufacturing techniques and better design software. In additio the designs changed through the years after studying the wearer's ergonomics and establishing which of the variable quantities of PAL design are more important in wearer's acceptance and happiness. These improvements can be used to minimize the sometimes antagonistic qualities of wearer adaptation and happiness.

The necessary information about wearer's adaptation and happiness can be learned from carefully controlled wearer trials. Unfortunately, most of the published wearer trials fail to provide much information about what makes a satisfactory PAL design. They compare designs of two or more manufacturers (competitors) that vary in too many ways and not only to one variable. Better-controlled wearer trials are needed but, unfortunately, most manufacturers would not provide such information for public use.

Also a general acceptable method is needed to provide the information of the optical qualities and performance of such lenses.

This chapter goes over the main designs of PALs, the way these designs are presented (contour plots) and what wearer trials have showed so far. Also, it shows the need of a general approved method for measuring the performance of such lenses and this is the subject of this thesis.

Chapter 2.

PAL Patent review

Introduction

Due to the large usage of progressive addition lenses in the last decades, a large number of different design patents have been submitted. All these patents represent the effort of researchers and manufacturers over the last 40 years, to provide a better lens for the correction of presbyopia. It is important to review these efforts and categorize them according to their aims. Also by knowing the different design philosophies it will be easier for someone to understand how these lenses work, in order to find a generally approve method of qualifying and assessing the performance of different design philosophies and market trends.

PAL Review

As it was mentioned in the previous *Chapter 1,* attempts to produce progressive addition lenses started in 1907 with the *Aves (1907)* design. In this design, the effect of the power progression was a result of the combination of two different optical elements. The next attempts can be categorized into two main philosophies.

a) The change in the dioptric power of the lens is accomplished by *changing the refractive index* of part or whole of the lens element used.
b) Producing the progression of optical power by *changing the curvature* of one of the front or back surface of the optical lens used.

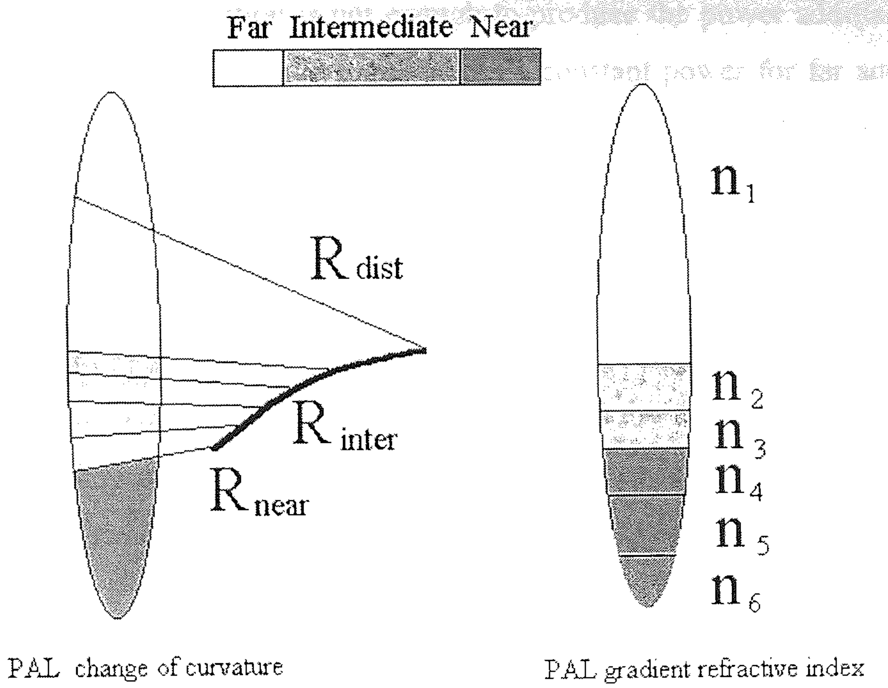


Figure 2.1. *The two different basic construction types of Pal's*

The patents submitted of the first type, where the multifocal lens was produced by incorporating a gradient index introducing an alteration of the dioptric power of the lens, proposed a method where the refractive index varied gradually and continuously through the whole lens element, or at a specific part of it, mainly the intermediate and near vision zones. All these patents used the diffusion method where a lens element was immersed into a bath of salts and by controlling the temperature they produced the index variation. The main lens element was either glass *(Spiegel, 1947)*, *(Hensler, 1970)*, or organic (plastic) where the diffusion was followed by polymerization *(Naujokas, 1969)*, *(Hamblen, 1969)*, *(Rosenbauer, 1971)*, *(Guilino, 1991)*. *Blum (1999)* had a similar approach only this time the power change was produced by a composite of at least three layers of different refractive index with the main lens blank.

All the above-mentioned efforts have never been commercially available so the success of this main philosophy remains unknown. The fact is, that according to a previous research of myself on this type of lens, the problems that they present are the reasons of not getting into the market. First of all the diffusion is difficult to control and direct, the index variation is not enough to produce the power addition needed, and finally it is difficult to have stable areas of constant power for far and near vision. Also, if the immersed lens has a round shape then you can get the power variation but astigmatic aberration still exists through the parts of index variation.

The patents submitted of the second type, are based on the fact that by changing the curvature of one or both of the lens surfaces it is possible to accomplish a change of the dioptric power presented by these lenses in part of through the whole aperture of the lens. This philosophy of design progressive addition lenses is the one that all manufacturers follow nowadays in order to produce commercially successful lenses.

But progressive lenses of this type also have well-known disadvantages. In particular, the intermediate-power zone invariably exhibits unwanted lateral astigmatism and focusing error. In addition, such lenses usually exhibit skew distortion (loss of orthoscopy), as well as unwanted power and prismatic imbalance in binocular viewing. These aberrations are unavoidable due to the principle concept design and much effort has been expended in attempts to reduce or minimize their effect.

There is another defect of such progressive addition lenses that is not often mentioned. Most progressive lenses, despite the feature of progressively varying power, are designed along the lines of a standard trifocal. That is to say, the distance portion of the progressive surface is spherical and occupies the upper half of the lens, just like the distance portion of a solid-type (Executive) trifocal; the reading area, too, is spherical, and occupies a segment-shaped area separated some 15mm from the distance vision area. These spherical distance and near vision areas are connected by a progressive corridor (the midline of which being usually an umbilic), and the inherent aberrations of the lens are compressed into the areas laterally disposed to the progressive corridor and the reading area. Not only are these aberrations objectionably strong (because the area into which they are packed is small), but the transition between the distance and intermediate areas, and between the intermediate and reading areas, is marked by relatively sharp changes in all optical characteristics: mean power, astigmatism and prism. Thus, the visual field afforded by the typical progressive lens is by no means a smooth and continuous one; rather, it is divided into alternately clear and blurred areas. Lenses which exhibit these discontinuous optical characteristics may not be tolerated by some patients.

In summary, the following may be cited as principle goals in the design of a progressive lens:

1. Optically stable and aberration-free distance and near-viewing areas.

2. Progressive corridor of useful width and convenient length.

3. Minimized surface astigmatism.

4. Minimized lateral power error.

5. Minimized skew distortion.

6. Minimized binocular power and astigmatic imbalance.

7. Minimized binocular vertical prismatic imbalance.

8. Visual continuity, i.e., smooth and continuous optical effect.

Unfortunately, it is not possible to satisfy all design goals simultaneously, and design compromises are inevitable. Many forms of compromise are possible, each leading to a new design with its own peculiar features.

Kanolt (1959) and *Volk (1971)* proposed a lens in which astigmatism levels have been reduced to relatively low values. This is achieved by distributing the astigmatism over the entire area of the lens, while the power increased from top to bottom of the lens. In Volk's design the progressive surface consisted of elliptical arcs. The total astigmatism presented outside the principal meridian was symmetrical at directions 45° and 135°. But the price paid is a heavy one; both the distance and near centres are objectionably astigmatic, and the power error at those levels is severe. Thus, while such a lens indeed displays visual continuity, too much has been sacrificed to attain it, and such a lens would not be acceptable to a wearer.

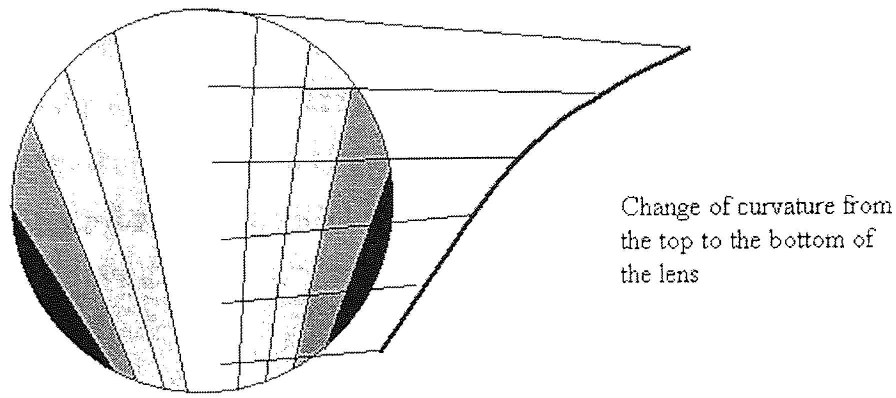


Figure 2.2. *Lens where the curvature changes continuously, and consequently astigmatic aberrations are spread over the entire lens surface.*

The most significant patents on progressive addition designs and their extremes were provided by *Maitenanz (1959), (1972), (1974), (1975)*. The first two patents describe the whole concept of producing a progressive addition surface while in the last he describes the two extreme design concepts that produce a progressive addition surface. He connects the known *hard lens design* (short progression corridor < 13-14 mm) with static vision and the *soft lens design* (long progression corridor > 14 mm) with dynamic vision. Their properties were described in Chapter 1 of this thesis. A pure *soft lens design* was introduced by *Maitenaz (1974)*. *Guilino (1982)* also produced a soft lens design in which the length of the progression corridor was 18 mm. *Maitenaz (1981)* again in order to produce a progressive surface used one surface S_1 with umbilical principal line, selected from certain family, which was combined with a non umbilical surface S_2 presented a vertical constant prismatic effect. The combination of the above surfaces S_1 and S_2 produces a lens with a wide corridor and a constant vertical prismatic effect, which means reduced oblique distortion.

The progressive lens described by *Winthrop (1977)* features a spherical distance portion occupying the entire upper half of the lens and a large spherical reading portion. Consequently, the astigmatism within the intermediate area is highly compressed and of non-negligible magnitude. Provision is made for the correction of orthoscopy in the peripheral portions of the intermediate area, but this feature results in an undesirable concentration of aberration at the boundary between the corrected and uncorrected areas. The layout of this design is similar to that of a trifocal, and consequently the design lacks visual continuity.

Guilino (1980) introduced a hard lens symmetrical design where the principal meridian of progression was not an umbilical one but the difference between the two main curvatures was very small. With this the far and near vision zones were widened considerably.

The design put forward by *Kitchen and Rupp (1981)* also features a spherical distance portion comprising the upper half of the lens, a large spherical reading portion, and correction for orthoscopy in the peripheral portions of the intermediate area. The astigmatism adjacent to the progressive corridor is reduced below normally expected values by permitting astigmatism to occur at the midline of the corridor itself; however, the astigmatism that remains to either side of the corridor is by no means negligible. Aberrations are highly concentrated at the boundary between those areas and are not corrected for orthoscopy. This design, conceptually similar to the one previously described, lacks visual continuity.

The progressive lens design described by *Guilino* and *Barth, (1982)* is similar to the two previously described designs in that it has a large, almost spherical distance portion and a large, almost spherical reading portion. In this design, less emphasis is placed on the maintenance of orthoscopy than in the two previously described designs. This permits slightly lower values of astigmatism and enables the astigmatism to be distributed more uniformly than in the previous two designs. Despite these improvements, the design still emulates the trifocal and consequently lacks overall visual continuity.

Davenport (1981), (1983) proposed similar progressive lenses in which the progressive surface is divided into the three traditional viewing zones, with a large, spherical distance portion in the upper half of the lens, a large, spherical reading portion in the lower half, and a meridional progressive corridor connecting the distance and reading portions. In the Davenport construction the progressive surface is generated by portions of a family of circles developed by passing an inclined plane of constant inclination through a multiplicity of spheres.

van Lighten (1982), (1984) proposed a hard lens symmetrical design with a wide corridor in the progression zone by incorporating at the intermediate zone two vertical lines which were umbilical while the area between them was aspheric but with astigmatism less than 0.50 D.

The progressive lens introduced by *Winthrop (1985)* reduces the astigmatism level of the traditional three-viewing-zone lens to an optimally low level by uniformly distributing the aberration in the intermediate zone through application of the Dirichlet principle. But this lens, like the lenses previously described, exhibits significant aberration and lacks visual continuity.

Each of the above designs is optically *symmetrical* about the corridor meridian and the actual design is a *hard* type. To enable the eye to track comfortably down the progressive corridor, the corridor of each lens must be inclined about 9 to 10° from the vertical when mounted in the frame. This, however, may lead to uncomfortable binocular inequity between the two lenses in off-axis viewing at the intermediate-power level. Some designs incorporate asymmetry (different lens design for the right and left eye of the wearer) about the corridor meridian in an effort to control these unwanted binocular effects.

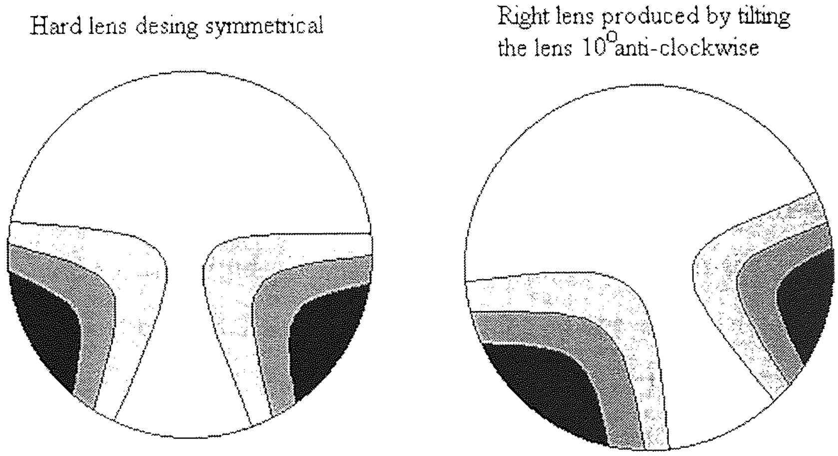


Figure 2.3. *Front view of a hard design of the symmetrical type, where the right or left lens was produce by tilting the same lens design by an angle in order to follow the convergence of the eyes when looking at near.*

Maitenaz (1974), proposed an asymmetric lens whose aim is to provide equal astigmatic effect binocularly at the intermediate and near power levels. However, the lens also features a spherical distance area comprising the upper half of the lens and a large spherical reading area. Consequently, although the astigmatic effects may be equalized binocularly, the magnitude of the astigmatism is objectionably strong. Moreover, the lens, being comprised of three distinct viewing zones in the manner of a trifocal, does not provide visual continuity.

The asymmetrical design introduced by *Fueter and Lahres, (1986)* aims to reduce to tolerable values binocular prism imbalance between the two lenses. But this design, too, has an almost spherical distance portion comprising the upper half of the lens, and a large, almost spherical reading portion. Consequently, the astigmatism at the intermediate level reaches significant values. Moreover, such a design, for the reason noted previously, cannot provide visual continuity.

Kitani (1988) proposed an asymmetric hard (14 mm) design. Here, not only the eyeball but also the head movement of the wearer is taken into account. So while the eyeball and head is turned towards a visual target located on a lateral side the wearer looks at such a visual target at an angle β. So the relation expresses angle β

$$\beta = \beta_{Head} + \beta_{Eyeball}\,.$$

From *Maitenaz, (1972),* it is known that the inherent astigmatism of progressive lenses can be reduced in magnitude by permitting it to extend into the peripheral areas of the distance portion. This reduction is attained at the price of introducing astigmatism and power error at the distance vision level. But the remaining astigmatism is by no means negligible. Moreover, despite the reduced levels of astigmatism, the structure of the design does not afford optimum visual continuity.

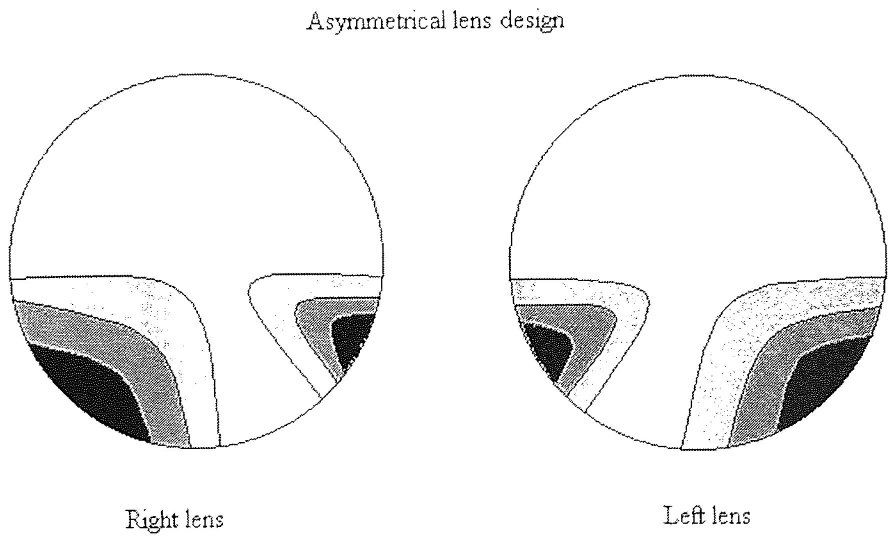
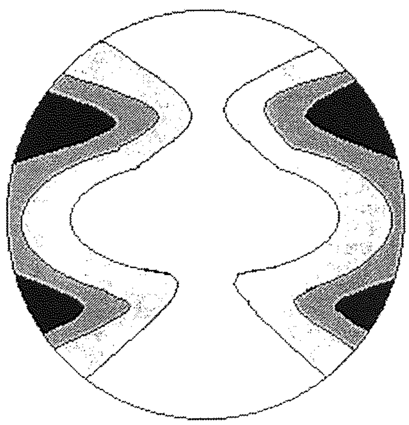


Figure 2.4. *Front view of a pair of progressive addition lenses where the right or left lens was produced separately for the right and left eye. The progressive channel is made for each lens in order to follow the convergence of the eyes when looking at near.*

The need for a specific type of progressive addition lenses, where the intermediate and the near vision are for main use, made inventors try to design lenses for specific tasks. These lens designs are for tasks such as for writing, medical operations like surgery, working with tools, computer-screen work *(Shinohara, 1988), (Furter, 1988), (Dufour, 1989), (Kitani, 1998), (Baudart, 2000)* or for half-eye spectacles for emmetropic presbyopes *(Barth, 1990)*. Besides the above specific use lens designs, *Winthorp (1992)* provided lenses for general purpose, occupational and dynamic activities. Depending on the type of intended use the meridional power law is selected so the lens is an 8th, 4th and 8th order polynomial power law. Also *Okazaki (1986)* introduced a lens for "daily use". The skew distortion in the outer areas of the intermediate zone was small, while the value of the astigmatism did not increase rapidly, but slowly.



Progressive addition lens for intermediate and near work

Figure 2.5. *Progressive addition lens where the intermediate and the near vision are for main use. The distance vision zone is limited but the intermediate and the near are large enough to facilitate the user in medium and near viewing distances.*

Shinohara (1985), (1986) proposed a lens design series where the qualities of both dynamic and static vision were kept equally high in the distance and intermediate vision areas, while the width of the near vision area was kept at a minimum acceptable value. In such a series of progressive lenses, there was a balance between the lens characteristics of static vision and that of dynamic vision. The lens series had a symmetrical design relative to the principal meridian, which was umbilical.

Another concept in lens design was the effort to present a horizontal symmetry across the entire lens. *FueGerhard (1986)* proposed a short progressive corridor lens design, where horizontal symmetry across the lens exists, which means that the same values of astigmatism and focusing error are present horizontally on each side of the corridor. The same characteristic was in the patents proposed by *Guilino (1990), Ueno (1991)* and *Kelch (1993)*for controlling the horizontal and vertical radii of curvature sideways of the principal meridian.

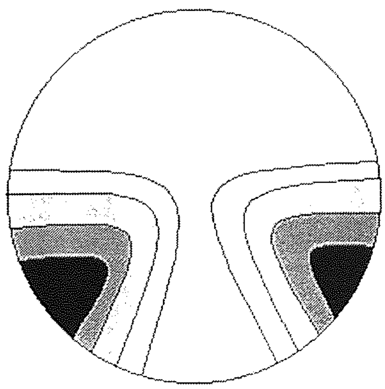


Figure 2.6. *A short progressive corridor lens design, where horizontal symmetry across the lens is apparent. The same values of astigmatism and focusing error exist horizontally on each side of the corridor.*

Shinohara (1986,) in order to reduce the chromatic aberration in the near vision area, and to make the lens thinner and lighter, tinted the lens with a colour consisting of yellow, brown and blue. In addition, he introduced a prism where its base was oriented in the direction of 90°. *Barth (1993)* introduced to the lens a vertical prism for reducing the thickness of the lens, having a size ranging from approx. 0.25 cm/m to approx. 3.00 cm/m. The same procedure was adopted by *Kato (1995),* where the lens was characterized in that a prism, having a magnitude Pt, was provided with a base in the direction of 90°, for reducing thickness, weight and aberrations. The power of the prism Pt was relative to the prescription for far and the add power. *Menezes (2003)* provided lenses, as well as methods for their design and production, in which prism power was introduced. This added prism power overcomes, in whole or in part, the adverse image quality effect of the lens un-prescribed prism power.

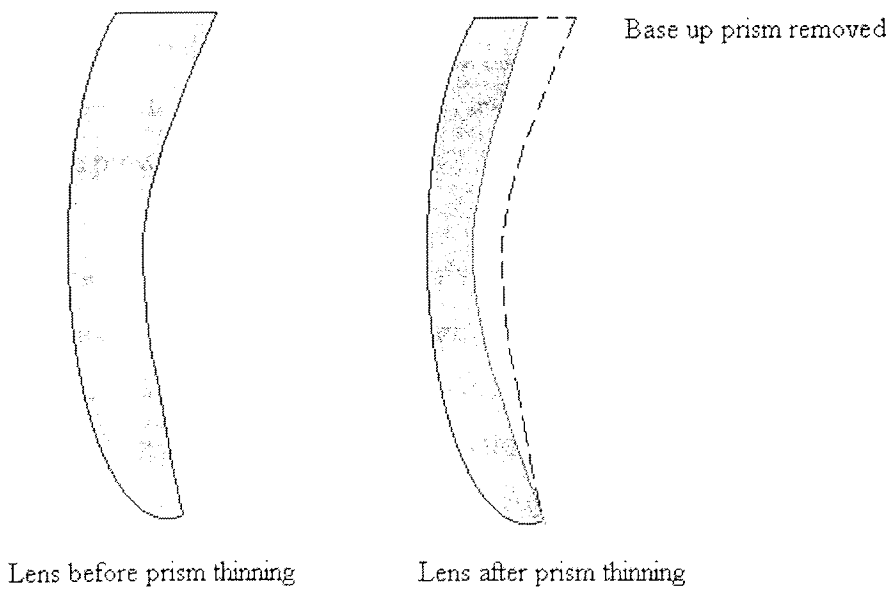


Figure 2.7. *The prism thinning process provides a more aesthetical side view of PALs*

Barkan (1987), (1989) used ray tracing, in order to permit adjustments for the intermediate and near zones. These adjustments could solve localized excessive astigmatism and distortion. He also computed the actual lens performance by ray tracing where ray obliquity was taken into account. He calculated 96 pre-selected points providing the best formulas for reducing surface and oblique astigmatism.

Dufour (1989) introduced the known concept of *multi-design* in order to provide a more comfortable adaptation from the wearer point of view when he changes his pair of lenses to a higher addition one. Until then the designs produced had either a constant length of the progression and an optical power progression gradient, which varied in order to achieve different addition, or a progression length, which linearly increased according to the addition but with a constant gradient of optical power progression. Depending on the increase of the value of the addition the progression length decreases also. *Ueno (1999)* with his design enables people with even high additions to comfortably continue to see short distances for a long period of time without eyestrain.

A different approach was presented by *Winthorp (1989)*. The distance and near zone power points comprise the poles of a bipolar system of surface power contours. The contours were selected in such a way as to achieve a smooth and pleasing distribution of surface power and astigmatism.

From the first commercial patents presented, the convergence of the eyes when reading at near was taken into account. *Maitenanz (1959)* proposed that the vertical axis of the lens (the "progression corridor"), in order to follow the pupillary convergence from far to near according to the function of the law of convergence – accommodation, had to resemble a curved line AB. Again *Maitenaz (1988)* had the main meridian displaced relative to the vertical plane passing through the optical centre of the lens towards the nose by about 0.8 to 1.33 millimetres. Such a lateral sliding motion of the main meridian provided visual comfort for intermediate vision and for near vision, without resulting in any excessive reduction of the area of far vision.

Kitani (1990) tried to solve the problem that exists with the convergence of the eyes during near reading. The main meridian connecting the distance and near vision centres was displaced toward the nose, while the displacement was varied depending upon the addition of the lens. If the addition was smaller than +1.50 D, the main meridian line lay above the straight line connecting the distance and near vision centres, while if the addition was larger than +2.50, the main meridian line lay below the straight line connecting the distance and near vision centres.

Pedrono (1993) takes into account the up and down position of the eyes in the ocular orbit and the posture of the wearer's head, the pantoscopic angle, the changes in the near viewing distance with increasing age and the ametropia of the wearer for distance vision. In order to provide a better progressive addition lens regarding the above, the principal meridian situated in the intermediate and near zones is divided into two segments. The first segment DC is inclined at an angle α to the vertical where the value of α is an increasing function of the power addition (A) of the lens, and the second segment CM', is inclined at an angle ω to the vertical where ω is smaller than α. At the point C where the two segments meet, the mean sphere value of the surface corresponds to a power addition laying in the range 0.8 to 0.92 times the nominal power addition of the lens. *Francois, et al. (2001)* proposed a lens design which improves the behaviour of the lenses in peripheral vision, for lenses which already have good foveal monocular or binocular vision on at least the principal line of sight or principal meridian. Such a lens ensures correct dynamic vision, and appropriate fusion of the images provided by the eyes outside of the static vision fields. In his lens design Francois takes into account the binocularity parameter. *Haimerl, et al. (2004)* proposed a lens where a change of binocular imaging properties with horizontal movements of glance is minimized. *Welk, et al. (2004)* proposed a lens very similar in concept to *Haimerl (2004)*.

Shinohara (1987), in order to eliminate the aberrations due to the base curve, selected bases depending on the ametropia of the wearer. The principal meridian curve of the lens is aspherical at the areas of distance and near zones ρt and ρs. At the centre points of the distance zone and the near zone, ρt= ρs. *Kelch (1995)* designed the lens according to the individual wearer requirements. The back surface, which is used as the prescription surface was an spherical surface without point and axis symmetry. If the shape of the frame and centreing are known, then the required prismatic actions can be distributed to the right and left lens in order to provide the best thickness and weight of such lenses. *Barth (1998)* proposed a convex aspherical front surface and a concave back surface having aspherical regions. The idea was to transpose the irritating surface astigmatism of the progressive front surface into an area where the power does not increase, this area being the zone for distance vision, while the astigmatism presented by the first progressive surface was compensated for by the astigmatism of the opposing surface. The lens was suitable for the so-called emmetropic presbyopes. *Altheimer (1998)* made the lens so the lines of equal surface power were horizontally passing over into the primary line, so rocking phenomena etc. are definitely avoided for the wearer in the event of a horizontal sighting movement. The concave side of the lens was made aspherical giving substantial cosmetic advantages, providing an enlargement of the area suitable for clear distinct vision. In *Pfeiffer's (1999)* lens design the second surface of the lens was an atoric surface of a rotational symmetry and had an astigmatic effect. The overall astigmatism along the main line was constant with regard to amount and axial position.

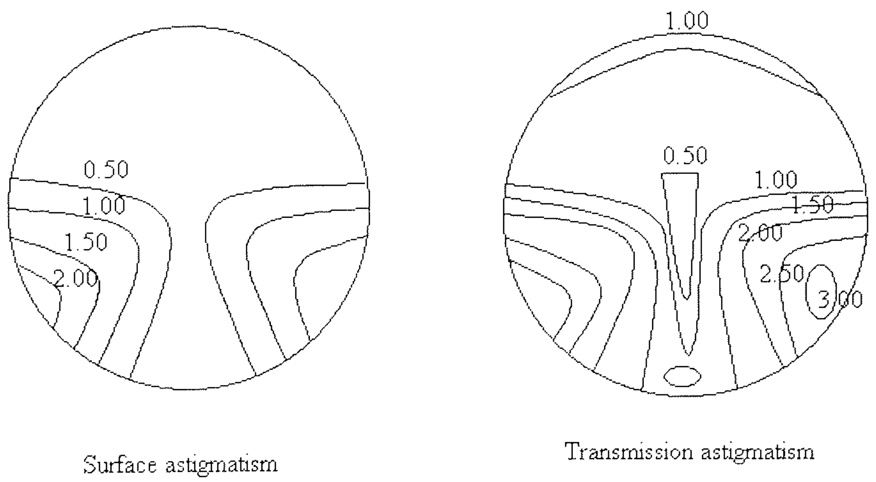


Figure 2.8. *The transmission astigmatism always has larger values than the surface astigmatism*

Kitani (1998) (2004) put forward a problem that should be considered in relation to oblique astigmatism. In a lens design, it is not the "surface average refractive power distribution" and the "surface astigmatism distribution" that evaluates the performance but the *"transmission average refractive power distribution"* and the *"transmission astigmatism distribution"*.

In an effort to minimize the astigmatic aberration presented by progressive addition lenses, lens designers try to find a compromise between hard and soft lens design. The ultra-soft lens design has the advantages of both the extreme designs mentioned above. *Harsigny (1996)* proposed such a lens where in the intermediate vision region, the isosphere lines are close together but substantially horizontal and peripheral vision remained comfortable. Ease of dynamic vision was preserved, for near and distance. The mean sphere gradient in the intermediate vision region was a linear function of the power addition value, while the effective progression length of the principal meridian is about 15 mm. The width of the near vision field measured horizontally at both sides of a point P -14 mm below the geometrical centre O of the lens along the y-axis where the dioptre isocylinder line was up to 0.50 D. *Umeda (1996)* reduced the maximum astigmatic aberration for intermediate and near while securing a sufficiently wide distinct vision area for distance. It was an asymmetrical design where the horizontal sectional shape at the lower portion of the distance vision portion increased and then decreased away from with the principal meridian. In the near it decreased and was then made approximately constant. *Ahsbahs (1998)* proposed that the width of the near vision zone varied not only as a function of power addition A, but also as a function of base curvature B used. The lens thus ensured, regardless of the extent of ametropia of the wearer and of the power addition of the lens, the provision of a substantially constant field of view in the near vision zone of the lens. *Kelch (1998)* introduced an aspheric non-axial-symmetric multifocal surface, which was differentiated continuously at least twice. The advantages claimed were an extraordinary width of the progression channel with a gentle increase of the astigmatism laterally of the progression channel, and a not too intense drop of the average power laterally of the progression channel and of the near zone. Also it has a thickness reduction prism with base at 270°. Furthermore the lens had a correct position for convergence within an elliptical region on the surface of the lens extending 50 mm measured horizontally and 40 mm measured vertically from the measurement point. *Mukaiyama (1999)* stated that the astigmatic aberration and difference of magnification of the first and second visual field areas could be reduced by adjusting the refractive powers of the first and second visual fields of both the surface on the side of the object and the surface on the side of the eye. *Le Saux (1999)* lens design had the principal length of progression shorter than 16 mm, while the cylinder within the 20 mm radius circle cantered on a geometrical centre of the lens was less than power addition, and preferably less than 80% of power addition. *Chauveau, et al. (2003)* introduced a progressive addition lens which provides wearers with improved peripheral vision while still ensuring foveal vision was good and consequently ensuring ease of adaptation of wearers to their lenses. The lens presented rapid progression of mean sphere, ensuring the presence of a large near vision region. It also provided balanced distribution of isosphere and isocylinder lines.

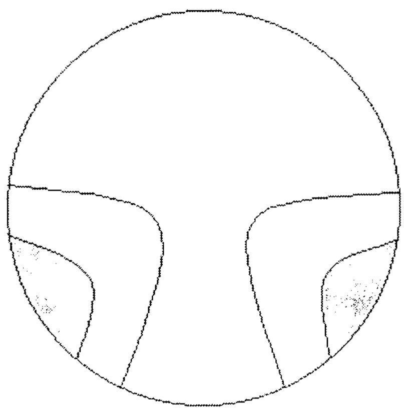


Figure 2.9. *Front view of an ultra-soft design where the benefits from the hard and soft lens design are kept regarding large distance – intermediate – near vision zones and low astigmatic aberrations with a small corridor length.*

Winthorp (1998) had a different approach in minimizing the astigmatism presented by PALs. The lens was a linear composite of a hard lens design and a soft lens design. The resulting lens design combined features of the visual utility of a hard lens design with the visual comfort of a soft lens design. A formula was given for the maximum astigmatism presented by the composite design:

$$A\ (max) = 1.5A - 0.75B$$

where A and B represent the addition of the hard and soft lens design used and B < 1.25.

Kaga (1999) followed a different approach in order to reduce astigmatism. The radii of curvature at main points of the lens progressive surface were calculated, and then the surface was divided into a plurality of lattice sections. Then a curved-surface equation in the form of a bicubic expression was used for each section to determine the surface shape of the lens. Since the curved surface could be determined for each section, a partial correction could easily be performed, if necessary. As a result, a progressive multifocal lens was provided which exhibits smooth astigmatism curves and a large clear field of vision to meet a variety of specifications.

Morris (1999) proposed that the base curve should be selected so as to be suitable for use in providing a range of distance prescriptions for myopes, and a second different set of lens designs for emmetropes and hypermetropes, each set containing elements with different addition powers. These lens designs from different sets had substantially the same addition power and substantially the same optical field of vision in the lower viewing zone. The corridor length may vary from approximately 19.00 mm to approximately 17.50 mm as addition power increases from +1.00 D to +3.00 D, and then increases to a value of approximately 18.25 mm above +3.00 D. *Morris (2000)* again proposed a similar lens design to the one of (1999) only that the visual fixation locus was inset generally horizontally nasally from the fitting cross (FC) of the lens a horizontal distance and extending obliquely down the corridor, the degree of horizontal inset decreasing with increasing addition power.

Kris, et al (2000) introduced lenses, which were designed with reduced sensitivity to horizontal fitting errors (such as errors in pupillary distance measurement of the wearer) and vertical fitting height errors related to frame and face conformation measurement errors.

Winthorp (2000) introduced a new lens design for use in frames having a vertical ("B") dimension <36 mm. The lens features a short (nominally 13-14.5 mm) progressive corridor and a novel treatment of the progressive optics that compensates for the distortion effects. The lens is defined by a circle of 30 mm diameter centred 2 mm vertically below the distance fitting centre in which the maximum value of unwanted astigmatism did not exceed the add value of the lens plus 0.25 D. A similar lens design was proposed by *Ahsbahs, et al. (2003) (2004).*

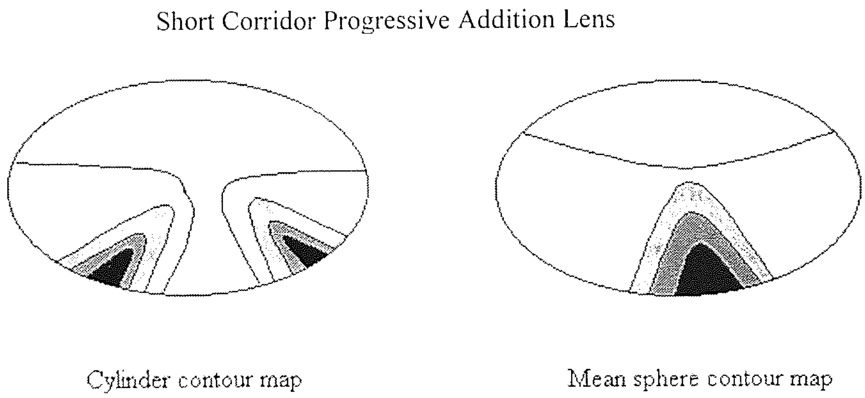


Figure 2.10. *A lens design for use in frames having a vertical dimension <36 mm*

Menezes (2000) (2004) (2005) proposed a composite progressive addition surface, which was formed by combining the designs of at least two progressive surfaces. Each of the two progressive surface designs had a maximum, localized unwanted astigmatism area or areas that are at different locations than those of the surface or surfaces with which it will be combined. When the designs of the two progressive surfaces are combined to form the composite surface design, the areas of maximum, localized unwanted astigmatism are misaligned. Because of this, the maximum, localized unwanted astigmatism of the composite surface is less than that of the sum of the contribution of the surfaces if the areas were aligned. *Menezes (2000)* again reduced the unwanted astigmatism by combining progressive addition and regressive surfaces. A regressive surface also had areas of unwanted astigmatism, the magnitude and axis of the regressive surface astigmatism were determined such as that the magnitude of the regressive surface astigmatism will be opposite in sign to that of the progressive surface astigmatism.

The latest trend in progressive lens design is to provide a lens design where the lens profile was made to suit the wearer's requirements. This means that the design is customised to each wearer individual needs. Such a lens design was introduced by *Menezes (2001)* where the channel power profile was made according to the wearer's requirements. *Baudart, et al. (2001)* provided a set of progressive multifocal ophthalmic lenses, taken into account the optical characteristics of the lenses, and particularly wearer power and oblique astigmatism, in worn conditions. *Yamakaji et al. (2003)* proposed a lens design which achieves a higher performance by designing the spectacle lens using a value determined for each individual spectacles wearer, such as a value of distance VR from a reference point on the back surface of a spectacle lens to the centre of rotation of the eye when the spectacle lenses is worn, which is one of the necessary data in the lens design. The same is proposed by *Welk, et al. (2003)* who proposed a lens design based on the objective that swaying sensations are avoided taken into account wearing conditions.

Menezes (2005) again proposed a different type of progressive addition lens comprising: a.) a distance vision power zone; b.) a near vision power zone comprising an add power; c.) an intermediate vision power zone between the distance and near vision power zones; and d.) a fourth zone located inferior to the near vision power zone, wherein the fourth zone has a constant power that is within about 20-25% to about 75-80% of the add power.

A more analytical review for each of the patents presented from 1907 up to 2005 can be found in Appendix I. All the details are given and the objectives for each patent submitted on progressive addition lenses in a chronological order. In this way someone can understand the evolution of PALs.

Summary

The knowledge of the evolution of progressive addition lenses is necessary in order to understand the basis on which these types of lenses are used and what they offer to the wearers of such type of lenses.

An awareness of lens design parameters is essential in predicting the optical performance of a progressive lens. Such parameters as, the useful progressive corridor width and convenient length, the aberration free distance and near vision areas, the surface and transmission astigmatism, the lateral power error, skew distortion, vertical prismatic effect and binocular visual performance are important in assessing and categorizing the lens designs that are present in the market. By knowing what to expect from these lenses it is easier to provide a method that will objectively provide the information about their performance. This method in our case is an interferometric technique which will give results on the main parameters mentioned above related to progressive addition lenses.

Chapter 3

Interferometry

Introduction

The first focimeters were originally designed to measure the vertex power of spectacle ophthalmic lenses and their optical centration. Over the years focimeters became slightly modified and could measure also the prism produced by a lens and the vertex power of hard and soft contact lenses.

Focimeters nowadays, although they are the main way of measuring ophthalmic spectacle lenses may also produce errors in the final reading. Especially now that the technology in producing ophthalmic lenses has evolved and more complicated surfaces are used such as aspherical and progressive addition, the need for a more objective and accurate measuring device is apparent. An alternative method better than focimetry is described, based on the phenomena of interference and the use of devices called interferometers.

Interference

When two or more waves simultaneously and independently travel through the same medium at the same time, their effects are superpositioned. The result of that superposition is called interference. *(Francon, 1966).*

There are two types of interference: *constructive* and *destructive*. Constructive interference occurs when the wave amplitudes reinforce each other, building a wave of even greater amplitude. Destructive interference occurs when the wave amplitudes oppose each other, resulting in waves of reduced amplitude.

The following is an explanation of how light waves interfere with each other. Consider a pair of light waves from the same source that are travelling, for example, in direction D. This is the propagation direction (as illustrated in Figure 3.1.) and if the vibrations (which are perpendicular to the propagation direction as represented by C in Figure 3.1.) are parallel to each other and are also parallel with respect to the direction of vibration, then the light waves may interfere with each other. If the vibrations are not in the same plane and are vibrating at 90° to each other, then they cannot interfere with one another.

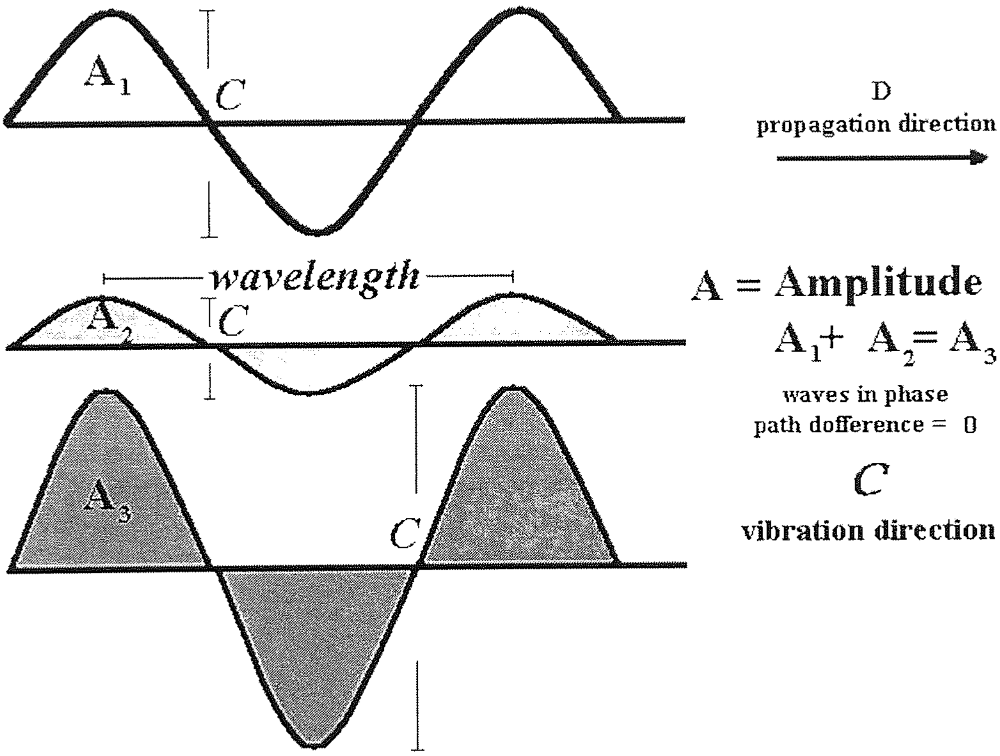


Figure 3.1. *Constructive interference*

Assuming all of the criteria listed above are met, then the waves can interfere either constructively or destructively with each other. If the crests of one of the waves coincide with the crests of the other, the amplitudes are additive. If the amplitudes of both waves are equal, the resultant amplitude would be doubled. Bear in mind that light intensity varies directly as the square of the amplitude. Thus, if the amplitude is doubled, intensity is quadrupled. Such additive interference is called constructive interference (illustrated in Figure 3.1.).

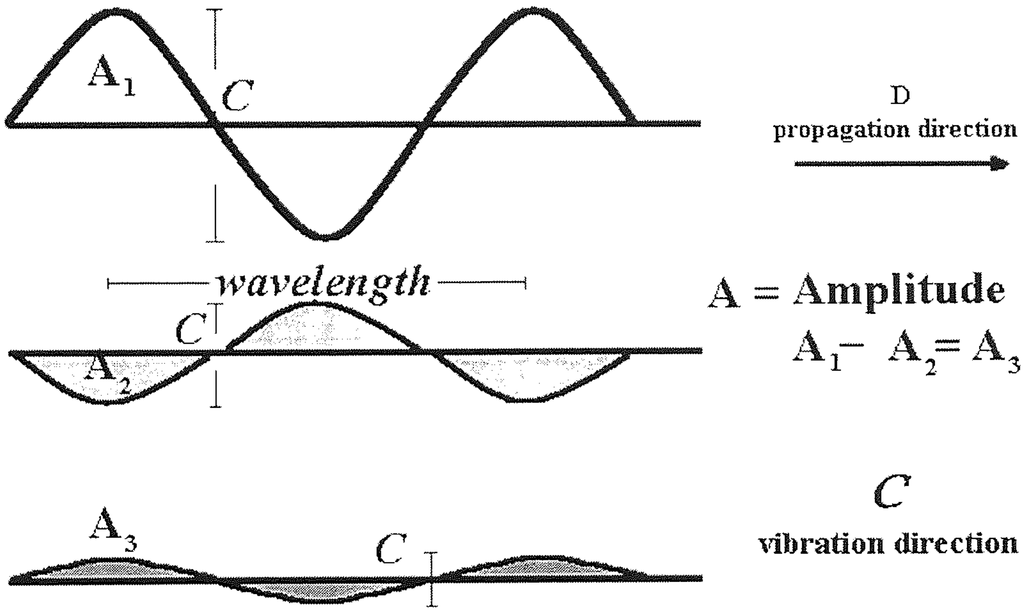


Figure 3.2. *Destructive interference*

If the crests of one wave coincide with the troughs of the other wave, the resultant amplitude is decreased or may even be completely cancelled, as illustrated in Figure 3.2. This is called destructive interference. The result is a drop in intensity, or in the case of total cancellation, blackness. *(Jenkins & White, 1976).*

It should be mentioned that it is impossible to obtain interference fringes from two different sources. The two new sources S_1 and S_2 derive from the same source S and always have a point-to-point correspondence of phase (Figure 3.3.). When the phase of the light wave from S_1 changes, then the phase of the light wave from S_2 will also change accordingly. It is understood that any phase difference between these two light waves remains constant and so the interference fringes are stationary. This characteristic of the two new sources S_1 and S_2 is called coherence and the sources coherent *(Steel, 1983).*

There are two ways to produce coherent waves in order to have interference. Young's experimental setup is the one, where two specific points of the first wave front are used in order to produce two new wave fronts (*wave-front division*). A coherent laser light illuminates a barrier containing two pinhole apertures that allow only some of the light to pass through. A screen is placed in the region behind the slits, and a pattern of bright and dark interference bands becomes visible on the screen. The resulting pattern on the screen is the product of interference between the two diffracted beams of laser light, and is often referred to as interference fringes (Figure 3.3.). The other way is by utilizing a beam-splitter, which is used in order to divide the first wave front into two separate components (*amplitude division*). *(Hariharan, 1992)*

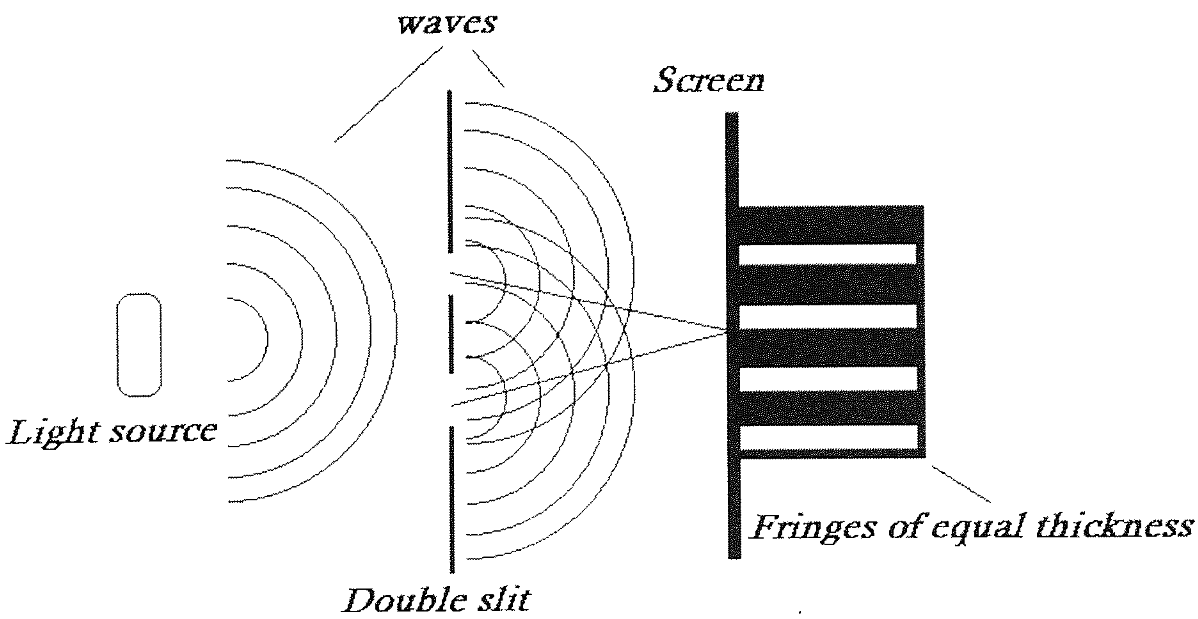


Figure 3.3. *Young's classic experiment, known as "the Double-Slit experiment".*

Interference intensity distribution fringes (such as those observed in Young's double slit experiment) vary in intensity when they are presented on a uniform background. The visibility (V) of the intensity is defined, as the difference between the maximum and minimum intensity of a fringe divided by their sum *(Jenkins & White, 1976)*:

$$V = I(max) - I(min)/I(max) + I(min)$$

where I (max) is the maximum intensity and I (min) is the minimum intensity. From the equation, idealized fringe intensity always lies between zero and one, however in practice fringe visibility is dependent upon the geometrical design of the experiment and the spectral range used. This is responsible for the myriad of interference patterns observed in naturally occurring events.

Interferometers are optical arrangements where a variety of precision measurements are feasible *(Hariharan, 1985)*. Interferometers are used in measurements of surface structure, pressure and temperature distribution in gas flows and plasmas but here we are only concerned in the set ups used to measure ophthalmic lenses *(Dyson, 1970)*.

An interferometer requires such an arrangement, where two or more beams, derived from the same source travel along separate paths, interfere *(Steel, 1983)*. These are called two-beam or multi-beam interferometers. The most well known types of interferometers used in optical testing are:

a) The Newton interferometer
b) The Michelson interferometer
c) The Fizeau interferometer
d) The Twyman-Green interferometer
e) The Mach-Zehnder interferometer
f) The Fabry-Perot interferometer

The first five types are classified as *two-beam* interferometers while the last one is a *multiple-beam* interferometer. A more detailed analysis of each of the above interferometric set-ups and their usage in optical testing is given in Appendix II.

Problems faced in measuring ophthalmic lenses with conventional or automated focimeters, and in the tests of evaluating their optical properties.

The first focimeters were originally designed to measure the vertex power of spectacle ophthalmic lenses and their optical centration. Over the years, and due to the evolution of technology in ophthalmic lenses (concentric aspheric surfaces, progressive addition lenses) the need for more accurate measurement was obvious. Actually conventional focimeters could only be slightly modified to measure the vertex power of hard and soft contact lenses but not very precisely. Conventional focimeters, unfortunately, might produce errors in the final reading of a spectacle lens because of the following factors

a) Eyepiece focusing

If there is a failure to focus the eyepiece of the instrument precisely it might give wrong readings, sometimes even more than 0.75 D.

b) The lens vertex position

Focimeters are calibrated assuming that the back surface of the lens coincides with the lens stop. With highly convex or concave lenses this might not be the case. According to *Bennett(1968)* we might have an error which may reach 0.12 D for a 20D spectacle lens. Most of the focimeters have a lens stop with an aperture of about 10 mm. This is also a problem with progressive addition lenses, which are very aspheric at the near section. A smaller aperture might help in order to reduce the sagittal height error that occurs. Otherwise the spherical aberration of the measured lens will become more apparent.

c) The use of filter

Many focimeters incorporate two filters for the illuminating target the 587.56 nm (helium “d” line) wavelength, and the 546.07 nm (mercury “e” line). Depending on which filter is used there will be a different measurement taken especially with high-powered lenses. *(Fowler et al, 2001).*

d) The quality of the standard lens

Any aberrations produce by this lens will affect the accuracy of the reading.

A lot of the above problems were solved with the use of the automatic focimeters, but these are very sensitive and sometimes if the surface of the lens is damaged might give us wrong readings, or even no reading at all. Automated focimeters have an obvious advantage over their human operated counterparts. When these instruments operate properly, they are not subject to the human factors of error.

Unfortunately there is the problem caused by the increasing use of high index glasses with their accompanying chromatic optical dispersion when measured with automated focimeters. In such a case, this property of dispersion can lead to optical error in the obtained measurement for high-power optical lenses. Such error can be in the range of 0.12 dioptre. Besides the chromatic aberration, information about oblique astigmatism and distortion is not revealed with conventional or automated focimeters.

Over the last twenty years the technology of spectacle lenses has become more sophisticated (progressive addition lenses, aspheric lenses) so there is a need for a more accurate measuring instrument. Unfortunately, when such lenses are measured by a focimeter (particularly an automated focimeter) the particular portions of constant power cannot be accurately located. Error in the measurement results when the lens is incorrectly placed. Further, and because there are no boundaries to guide measurement, such misplacement is a frequent occurrence.

Also, there is the prism thinning process as a lens processing method, called *Prismatic Thinning*. The prism thinning process is for thinning a thickness of a progressive focus lens, particularly of the far viewing section of the progressive focus lens. In the method, a plus-lens is applied with a down-prism process and a minus-lens is applied with an up-prism process. However, after the prism thinning process, the geometric centre is not equivalent to the optical centre and the prism quantity is dislocated, so that an exact measuring point of the far viewing section could not be determined.

From the above it is obvious that an alternative method with more accurate measurements should be provided which will be fast and effective in evaluating the optical properties and performance of more sophisticated ophthalmic lenses. This alternative method utilizes the theory of interferometry and the device is an interferometer of the previous mentioned types.

Unfortunately all the information so far given about the interferometric methods used in optical testing does not reveal the practical techniques and final results in testing ophthalmic lenses and especially in complex surfaces such as aspheric used in progressive addition lenses.

The Foucault test and the Ronchi test used in the first half of the 20^{th} century were powerful device methods revealing invisible faults and defects that an optical element might have. Unfortunately these methods have a subjective nature and are difficult to assess on complex surfaces like the aspherics lately used in ophthalmic lenses. The Foucault test is qualitative in detecting errors on an optical surface but the magnitude of these errors is not easily measured. Interferometry compared with the above two tests can be more objective in its results and their magnitude through computer analysis, avoiding the errors produced by an inexperienced observer.

Interferometry offers many advantages over the Foucault and Ronchi tests, but due to the expensive equipment used, like lasers, it did not have the treatment that it deserves from the optical community. Now that the lasers are not that expensive, this method should be given the opportunity to prove its effectiveness. With interferometry the light beam coming from the surface under test (the test wave front) is compared with the light beam coming from a reference surface (the reference wave front) of known properties and quality. When the two wave fronts are combined, interference fringes are formed revealing the optical quality of the surface under test. The interference pattern provides *qualitative* and *quantitative* information after measuring the spacing of the fringes. Unfortunately, problems that have to be solved when using an interferometric set-up are the influences that there are on the fringe pattern from air currents, temperature variations and vibration. These can make interferometry difficult as a method. So it is necessary to have solid optical mounts and base to reduce vibrations, and controlled room conditions related to air currents and temperature.

From the Appendix II it is understood that the simplest interferometer to make is the Newton interferometer. In such a device the test and reference surfaces are in contact, while the fringe pattern presented is due to the air space introduced between the test and reference surface, and can be viewed by the observer only.

The main disadvantage of the Newton interferometer is that the surfaces have to be in contact and there is a possibility to scratch these surfaces when they are in contact. Also the testing provided deals with only the two surfaces in contact and not the entire optical element, so it is impossible to asses the whole optical element tested for its optical quality and performance. It should be considered that the two surfaces in contact should be thoroughly cleaned and no dust or particles being in between them.

The Twyman-Green interferometer, which is a modification of the Michelson interferometer, solves the above mentioned problem faced with the Newton one. The monochromatic light coming from the laser source is collimated by a lens providing parallel wave front, which is used as the reference wave front to compare with the wave front produced by the optical element tested. With the Twyman-Green interferometer it is feasible to produce fringe patterns without having the tested optical element to be in contact with a reference one. The Twyman-Green interferometer requires the usage of a very high quality beam splitter and mirrors otherwise all the defects will be carried to the fringe pattern .

The Fizeau interferometer is another type which can be used in optical testing. The main difference with the Newton one is that the light beam coming from the source is collimated using a collimating lens. The Fizeau was limited to testing flats in near contact, and the air space between the two surfaces should not be more than a millimetre or so. Again only the individual surfaces can be checked and not the entire optical element.

From the above and from the literature review of the types of interferometers it is considered that the Twyman-Green set-up would be the best to be used in order to assess progressive addition lenses. The need for a non-contact interferometer of the simple two-beam type is also one of the reasons of ruling out the Fabry-Perot type. The Mach Zender type could also be a choice due to the fact that the measurement wave front transverse only once and the separation of the beams can be made as large as desired, but from the literature review (Appendix II) it is understood that this type of device is good for studies of gas flow or heat transfer. Also, the set up is not any more a simple one, having to adjust more components, which makes it difficult to achieve.

Important factors in the use of interferometers in optical testing

a) The alignment of the interferometer components

The optical components of the interferometric set-up must be aligned in order to have all the optical elements at the same height and centered. All optical element placement in the system is related to the height of the laser. Also, the laser must be checked to be parallel with the ground table on which the set is placed. This is best done in a dark room in order to easily trace the beam coming out of the laser passing through the rest of the elements of the set-up.

b) Methods to project, view and record the fringes

The room where the interferometer is set should be dark in order that the fringe pattern is easily visible. The fringes are projected on to a screen with a grid-ruler placed at a distance from the beam splitter and at the same plane passing vertical from mirror M_1. The screen should be placed as far as possible from the beam splitter in order to make the fringe pattern larger and easily visible. If the fringes are very small to see then a magnifying lens element is used to enlarge the pattern.

The fringe pattern can be recorded either by a video camera or a digital camera or even with a conventional photo camera. In this way the pattern can be studied later or it can be transferred on to a computer for a more elaborated analysis. It is important that the camera is focused properly on the viewing screen and should also be aligned with it. It is better to put the camera just behind the screen and must not be at an angle to it. The magnification of the fringe pattern is of great importance providing greater and better accuracy of the measurement taken.

c) The right analysis of the fringe pattern

All the information needed in optical testing is carried on to the fringe pattern. So its analysis will give the proper accuracy in the measurement. The quickest way is by the observer but it carries the subjectivity of the way that the observer sees the pattern. The fringe pattern carries all the qualitative and quantitative information that someone needs in order to analyse the performance of the tested element. If the aberrations presented by the fringe pattern are simple then the interpretation of the pattern is easy. But if the tested element is complex, then computer software is needed in order to analyze it. This will eliminate the subjectivity of the observer and will be more accurate and faster to interpret. This means that the fringe pattern should be transferred on to the computer either by scanning it, or direct transfer from a digital recording medium. These modern tools, interferometry and software analysis of the fringes, provide a truly objective measurement of an ophthalmic lens making it possible to assess its performance.

Summary

Conventional and automated focimeters are mainly used in assessing the performance and in measurement of progressive addition lenses. The problems presented when measuring such complex lens designs and the fact that the information given is limited regarding their optical properties urge for a new method simple in concept and construction that will reveal the properties of such lenses.

A Twyman-Green interferometer (two-beam) is proposed as a set-up in order to give all the *quantitative* information of such lenses. The fringe pattern produced and its analysis provides an objective assessment revealing the information needed for the experts to interpret. But it is good to have in mind that this interferometric technique is not actually an easy one and it also hides problems that have to be resolved in the future.

Chapter 4.

Experimental set-up and method

Introduction

A method and its validation are presented for measuring the total power of single vision trial spherical and cylindrical lenses. Although initially a Michelson interferometer was used for the measurements, from the results it was seen that the final interferograms were influenced by aberrations and the power of the initial wave front (reference wave front) produced by the laser, and the expanding beam lens used in front of the laser in order to get as much surface of the lenses tested. Also it was understood that in order to get the actual information on performance from the fringe patterns when testing single vision lenses then the optics used, that means the mirrors, the beam splitter, and the lenses in the set-up should be of excellent quality.

Although with the Michelson interferometer information about the power of the lenses tested could be provided, due to the fact that the reference wave front was not plane this produced an error in the final result, which was carried in all the measurements. It was a systematic error that could be calculated but in order to get the actual information needed from the interferograms taken, a Twyman-Green interferometer was preferred, which provided a reference wave front, which was plane. Information also is given about how the fringe patterns were captured and interpreted (the equation used) in order to get the total power result of the single vision tested lenses. Also the validation of the method and the repeatability of the results were tested in order to establish the final technique to measure progressive addition lenses.

This method was going to be used in measuring the power of progressive addition lenses providing information on how the power is distributed in such complex ophthalmic lenses.

From the literature a Michelson interferometer was first built up in order to measure the power of single vision lenses. As was mentioned in Chapter 3 and Appendix II the simplest device to use interferometry is the Newton one. A modified version of it is the Fizeau interferometer, which actually is a collimating Newton intereferometer.

The principal concept was to use a simple, low cost and easy to operate interferometer, with the least complexity in its set-up, in order to get accurate measurements on the power of ophthalmic lenses and especially of progressive addition lenses. Although the Newton interferometer would be the first choice from the literature it was understood that only one of the surfaces would be measured and not the whole lens. Also this type is a contact interferometer. These were the reasons that the Newton and Fizeau (modified Newton) interferometers were ruled out and not chosen for such an attempt.

As an experimental device a Michelson interferometer was the first choice in order to get fringe patterns of optical components, like prisms, spherical and cylindrical lenses. From the interferograms and their interpretation the power of the lenses tested could be derived. Figure 4.1. is a schematic representation of the experimental set up for such a purpose.

As it is seen in Figure 4.1 a He-Neon laser (red) having a transmitting wavelength of 632. 8 x 10^{-6} mm and with a beam diameter of 0.8 mm is used. The laser is set onto two metallic tables with 50 cm length and 35 cm width. These two metallic tables, which are heavy enough, were put one on top of each other in order the whole set up to be stable. This was done to avoid vibrations affecting the fringes .

After the laser, a + 50 mm lens was placed at a distance of 13 cm. This lens was put in the path of the laser beam in order to expand it. With an expanding initial beam a larger surface of the trial lenses inserted in to the interferometric system will be tested.

After the lens at a distance of 21 cm a beam splitter was placed oriented at 45° to the laser beam direction. The splitter was put there in order to divide the initial laser beam into two other components, one reflected and the other transmitted. The angle of the splitter related to the laser beam propagation and to the two mirrors of the system is very important. It should be placed as mentioned 45° to the plane of the beam propagation and containing mirror M_2 and related to the plane vertical to mirror M_1.

After the beam splitter and at a distance of 19 cm a movable mirror M_2 (its movement was controlled by a screw altering its position) was placed while a mirror M_1 was placed perpendicular to the beam propagation. The mirrors have a diameter of 35 mm, which is the same as the diameter of the trial lenses tested.

On the opposite side of mirror M_1, a + 100 mm lens was placed at a distance of 16 mm from the beam splitter. This lens was placed there in order to magnify the fringes so that these are visible on the target screen, which was placed on one of the walls of the lab at a distance of 2.5 metres.

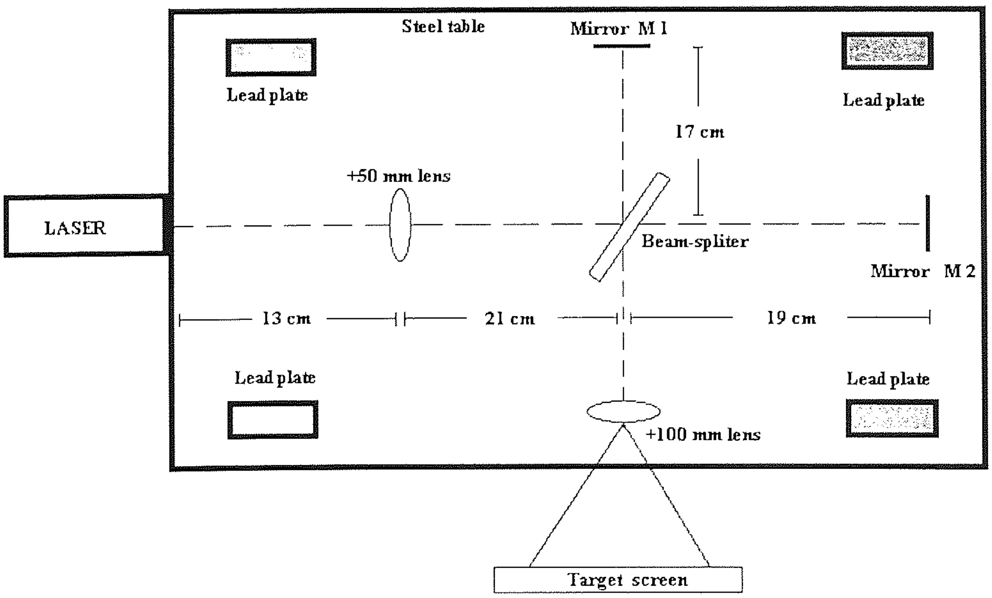


Figure 4.1. *Schematic diagram of the first attempted experimental device constructed in order to measure ophthalmic lenses with interferometry.*

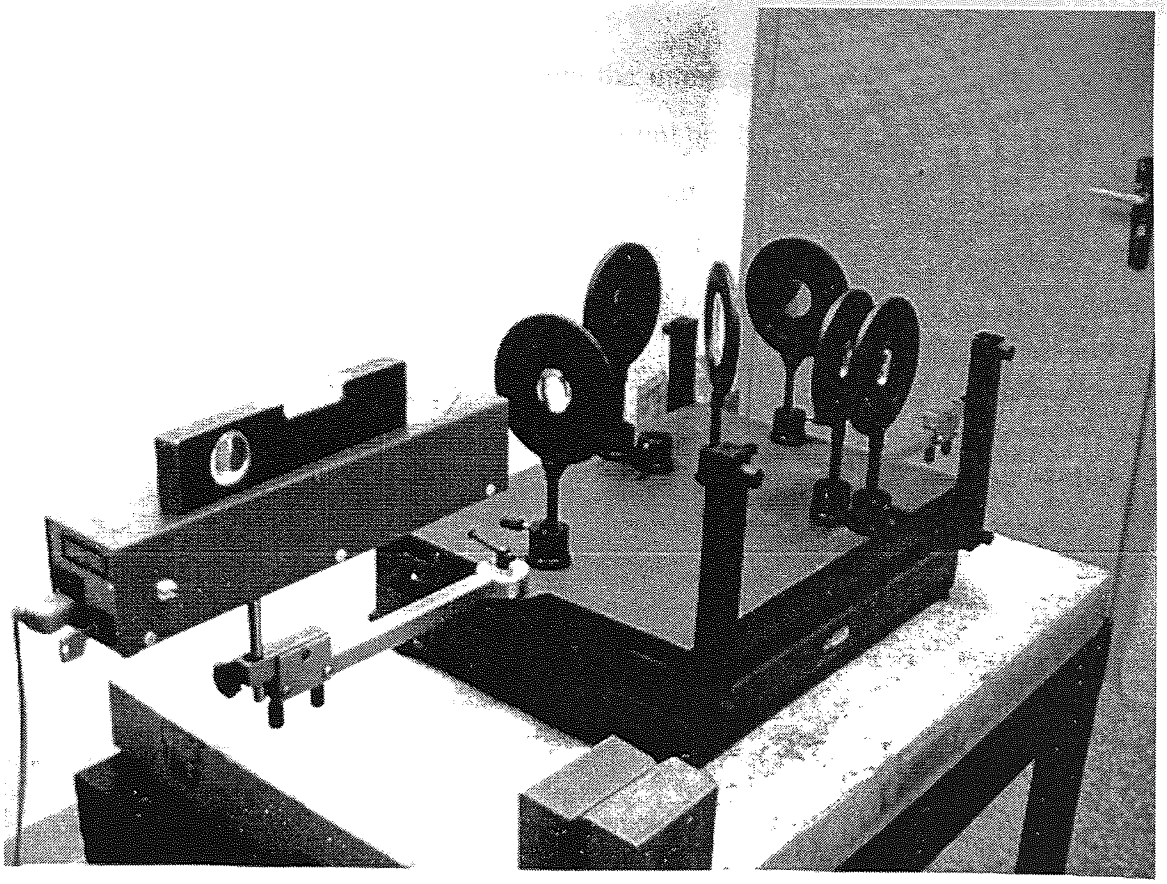


Figure 4.2. *Phtotgraph of the lab and the set-up of the interferometric device.*

The use of the lead plates, the heavy metallic tables and the granite table, in total two tonnes of weight, was necessary in order to reduce the interfering of vibrations on the device and on the fringe patterns produced. Even the least noise or air current could affect the fringe patterns producing a breathing phenomenon. The lab was provided by the Dept of Physics of TEI of Athens as well as the equipment needed. Also all the measurements were taken late afternoon in order to avoid as much as possible the noise vibrations coming from outside the lab room.

Instead of using the granite table to isolate the noise, a cushion a rubber filled with water could be utilised, which will absorb the vibrations. Unfortunately this was difficult to construct so the heavy table was the solution to vibration isolation. Also the air turbulence and the temperature changes affect the fringe pattern stability, which is why the lab did not have windows producing air currents and the temperature was checked to be as stable as possible.

The most difficult part at first was to align the interferometer so all its components are at the same height level. The first part to mount on the set-up was the laser. It was hold firm on an arm of the metallic tables used and it was tested to be parallel with the ground. With the laser on and the room dark the remaining components were inserted on to the set. First the expanding lens +50 mm was put it in the system and the optical centre of the lens was aligned with the laser beam. Then the beam splitter was inserted, placed at exactly 45° angle with the laser plane. Then the two mirrors also centered at the two-produced beam after the beam splitter. All the optical components were cleaned before inserted with alcohol in order to have no dust interference.

A luxometer was used, in order to measure the intensity of light at different places in our Michelson set up. According to the measurements in front of the laser the intensity of light was 10 lux on the scale of 300. After the beam splitter to the direction of mirror M_1 5.6 lux on the scale of 100, while to the direction of mirror M_2 it was 4.2 lux on the scale of 100. The intensity of light on the screen, where the fringes are observed, varied from 2 lux to 8 lux on the scale of 10. In order to photograph the fringes a manual ZENITH camera , was used with a 35 mm lens and a zoom lens. The camera was set at a distance of 2.5 m from the screen and at an angle of 45° from the perpendicular to the screen. This procedure was carried out in order to evaluate the possibility of photographing the fringe patterns produced each time and the best way of taking photographs manually.

First, the fringes were photographed without having any optical element placed into the interferometer system. Different exposure times were used (5 sec., 15 sec., 30 sec., 45 sec.) in order to assess which will be the best exposure time for bright fringe patterns. The exposure time of 15 sec having set the camera shutter to 'B' and an aperture of 2.8 gave the best clear photos of fringes. In order to get fringes of equal inclination (circular) the movable mirror M_2 was tilted using two screws for its directional movement (horizontal and vertical). With this set-up the initial wave front should be spherical if all optics were of fine quality. After that in front of mirror M_1 prisms were placed (from a trial case) at a distance from the mirror of 5 mm on a lens holder with 1 D prism 2 D and 3 D prism in order to assess how the system will react, and if it is possible to measure prismatic lenses. Then optical flats were used (1 mm thickness, 5 mm thickness, 8 mm thickness, 10 mm thickness) in order to assess if the thickness of an optical element is affecting the fringe pattern.

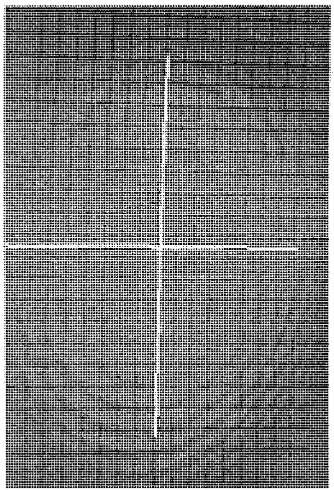
After the above, trial lenses were inserted into the system from the trial case and measured. Spherical lenses (-0.50Ds, -1.00 Ds, -2.00 Ds, -3.00 Ds, -4.00 Ds, +1.00 Ds, +2.00 Ds, +4.00 Ds) and then plano-cylindrical lenses (-1.00 Dc., -2.00 Dc., -4.00 Dc, +1.00 Dc., +2.00 Dc., +4.00 Dc.). The fringe patterns were photographed and scanned in to a computer in order to calculate the power of the known prisms and lenses. The following equation was used in order to find the power of the spherical and cylindrical lenses tested

$$x_n^2/R = n\lambda \Rightarrow x_n = \sqrt{n R \lambda} \Rightarrow R = x_n^2/n\lambda$$

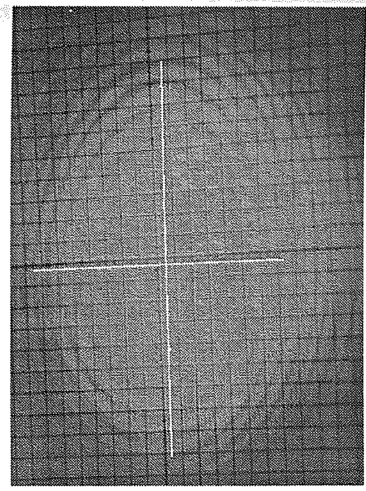
where x_n is the distance of the nth dark fringe R is the radius of curvature of the optical element under test n is the number of the dark fringe from the centre of the fringe pattern while λ is the wave length of the light source used ($\lambda = 632.8 \times 10^{-6}$ mm).

The prism power was derived by measuring the displacement dx of the centre of the circular fringe pattern from the centre of the grid with the metric scale. At first the displacement of the prism of 1 D was measured. Then 2 D prismatic power and 3 D were inserted in the measurement system and it was found that the displacement was 2x times or 3x times the displacement distance of the 1 prismatic dioptre lens.

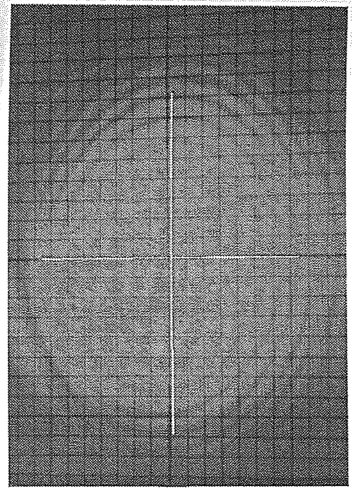
Figure 4.3. shows the fringe pattern photographed with no optical element inserted in the system compared with the fringes when flats were inserted with 1, 5, 8 and 10 mm thickness and a prism of 1 D.



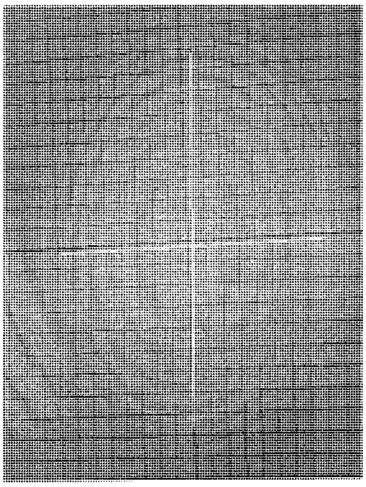
without lens



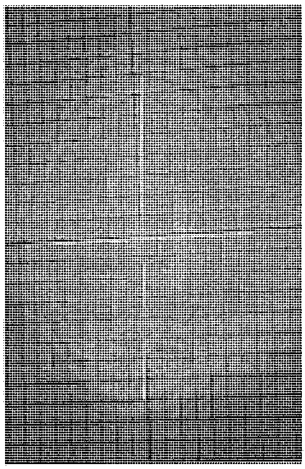
Flat 1mm



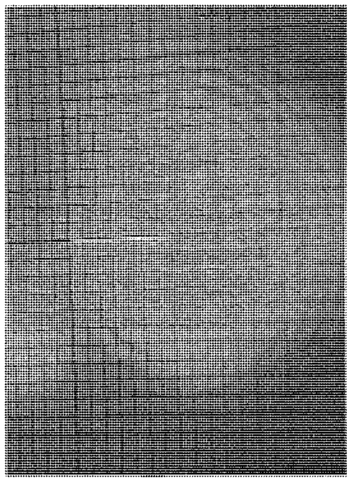
Flat 5mm



Flat 8mm



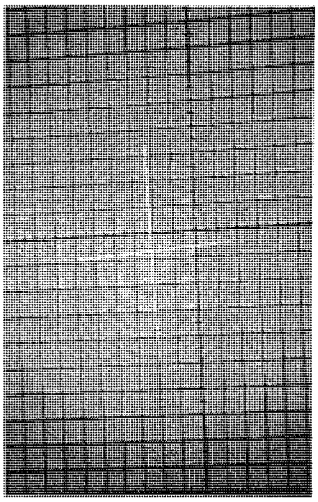
Flat 10mm



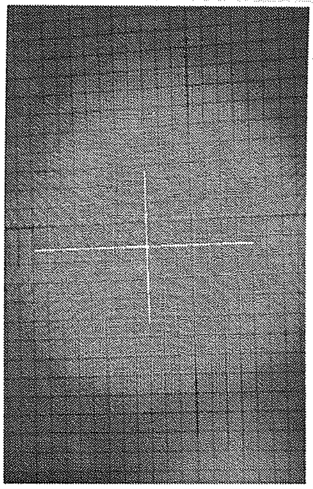
Prism 1 D

Figure 4.3. *The fringe patterns produced with the Michelson interferometer. As is seen from the patterns the insertion of a flat it does not affect the fringe pattern nor its dimensions when the thickness of the flats changes. With a prismatic lens also the fringe pattern does not changes only there is a displacement of the centre of the fringes towards the base of the inserted prism. The displacement is analogous to the prismatic power of the trial prism inserted onto the system.*

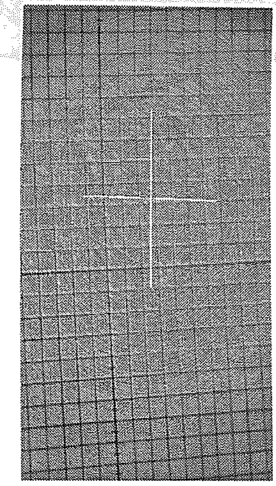
The system also was tested with spherical and cylindrical lenses from the trial case. In each fringe pattern the diameter of the 5^{th} circular fringe was counted at an x and y-axis. Figure 4.4. shows the fringe patterns for trial lenses tested with the first constructed system.



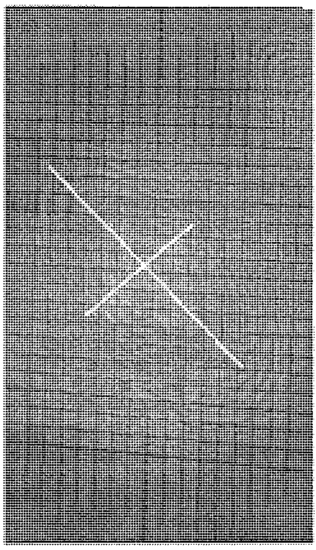
+ 1.00 Ds



+1.00 Dc



- 1.00 Ds



- 1.00 Dc

Figure 4.4. *Fringe patterns of trial lenses tested with the first system set-up*

Table 4.1. provides the measurements on each of the above interferogram after assessing the curvature of the wave front compared with the initial wave front with the system without lens element inserted.

Table 4.1a

Lens type.	*Distance 5th fringe (x) axis.*	*Distance (y) axis.*	*F1*	*F2*
No lens	175	180	*0,253*	*0,239*
Flat 1mm	150	180	*0,344*	*0,239*
Flat 5mm	150	180	*0,344*	*0,239*
Flat 8mm	175	180	*0,253*	*0,239*
Flat 10mm	150	165	*0,344*	*0,284*
+ 1.00 Ds	90	80	*0,957*	*1,211*
+ 1.00 Dc	140	80	*0,395*	*1,211*
- 1.00 Ds	75	85	*1,072*	*1,378*
- 1.00 Dc	135	75	*0,538*	*1,582*

Dimensions of fringe pattern from photographs (mm). F1 and F2 represent equivalent maximum and minimum calculated powers (D).

The magnification required for making the fringe patterns visible and to be able to be photographed was 35x for the fringes for no lens, the flats, the prisms, and the spherical and cylindrical lenses. For prism with 1 D the displacement of the centre of the circular fringes from the centre of the metric scale screen it was 60 mm for 2 D was 120 mm and for 3 D 180 mm.

As is seen from the above Table 4.1. it is observed that with such a system as the Michelson interferometer:

A) We can measure the prismatic power safely by measuring the deviation of the centre of the fringe pattern from the initial (before a prism is installed in the system) at the centre of the metric scale of the screen.

B) The thickness of the optical element does not affect seriously the results.

C) It is possible to measure the power of the lens tested against the initial spherical wave front produced by the Michelson but as can be seen from the results the initial wave front is an astigmatic one affecting the final measurements with spherical and cylindrical lenses. This astigmatic power of the initial laser beam is carried through to all the results of the lenses measured. It is believed that this aberration was observed also due to the fact that the fringe patterns were photographed at an angle from the perpendicular of about 45°, which gave a distorted fringe pattern and so created an additional problem with the one of not having a spherical initial wave front.

D) Another problem faced was the breathing of the fringe pattern. The fringe pattern is very sensitive to noise destruction so it is not stable. Making the system heavier by utilizing the granite table solved partially the problem.

The next attempts were:

A) To calibrate the experimental device by collimating the initial beam from the laser (Twyman-Green interferometer) in order to have an initial plane wave front, when there was no lens in the system. This would be our reference wave front for comparison with the one produced with an optical element inserted on to the system of the Twyman-Green interferometer.

B) To photograph the fringe patterns produced by the new set-up interferometer (Twyman-Green) introducing a change in the style of the photographic technique used. The camera was placed just behind the screen directly aligned with its centre. The exposure time, due to the direct alignment of the film with the fringe pattern (the camera is set 1 m away from the transparent grid), was quicker (better photographs taken by setting the camera with a shutter speed of 1/125 second, and the aperture set at 2.0).

Figure 4.5. shows the Twyman-Green interferometer used in order to measure lenses. It is actually like the Michelson used before only a lens of focal length +100 mm is inserted into the system in front of the laser at a distance of 10cm at the first principal focus of the lens. This is done in order to make the initial laser beam a plane wave front (parallel rays) which would be the reference wave front for comparison with the one produced by any lens element inserted into the system.

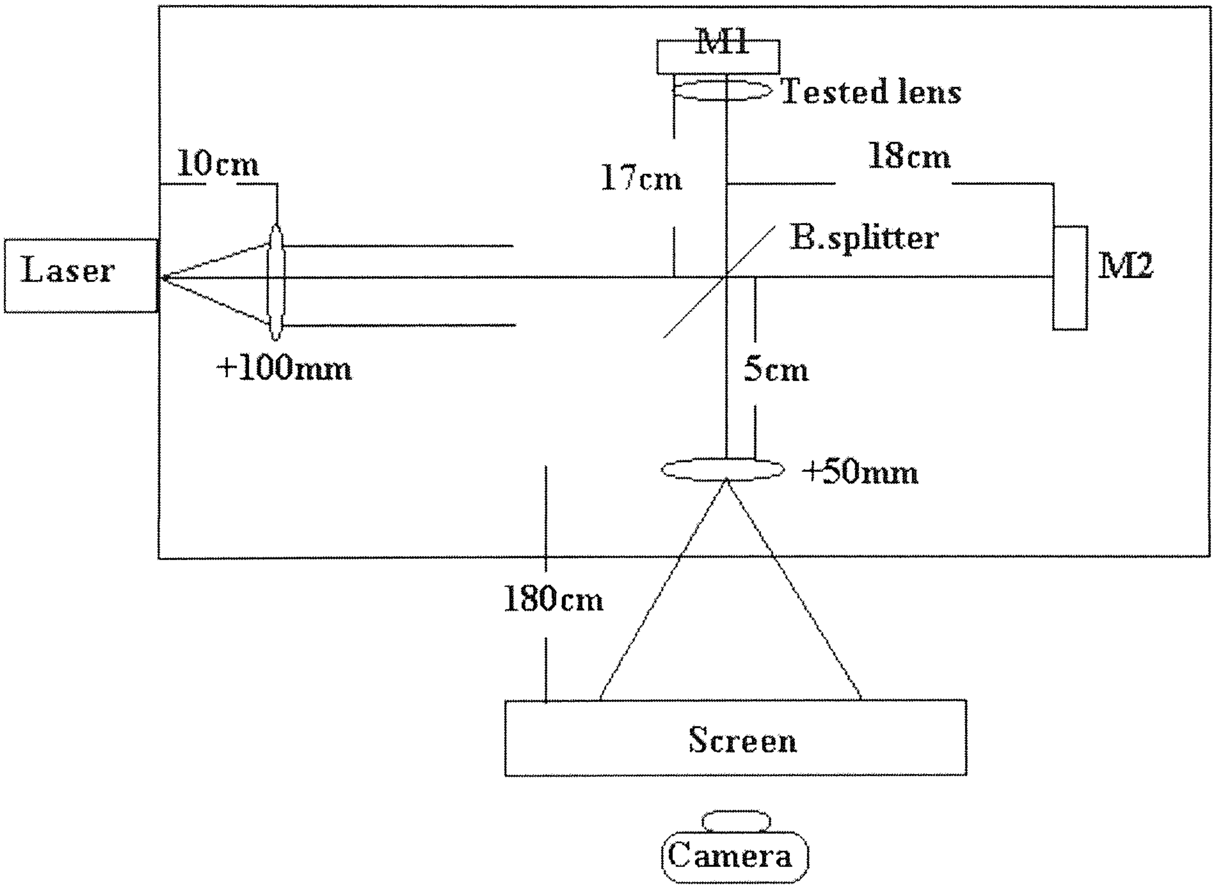


Figure 4.5. *Schematic diagram of the second attempt experimental device constructed in order to measure ophthalmic lenses with interferometry. It is a modified version of the first set-up only a collimating lens with a focal length of +100 mm was placed in front of the laser at a distance equal to its first focal point in order to produce a plane initial wave front. Also the camera was placed in alignment with the screen where the fringes were projected.*

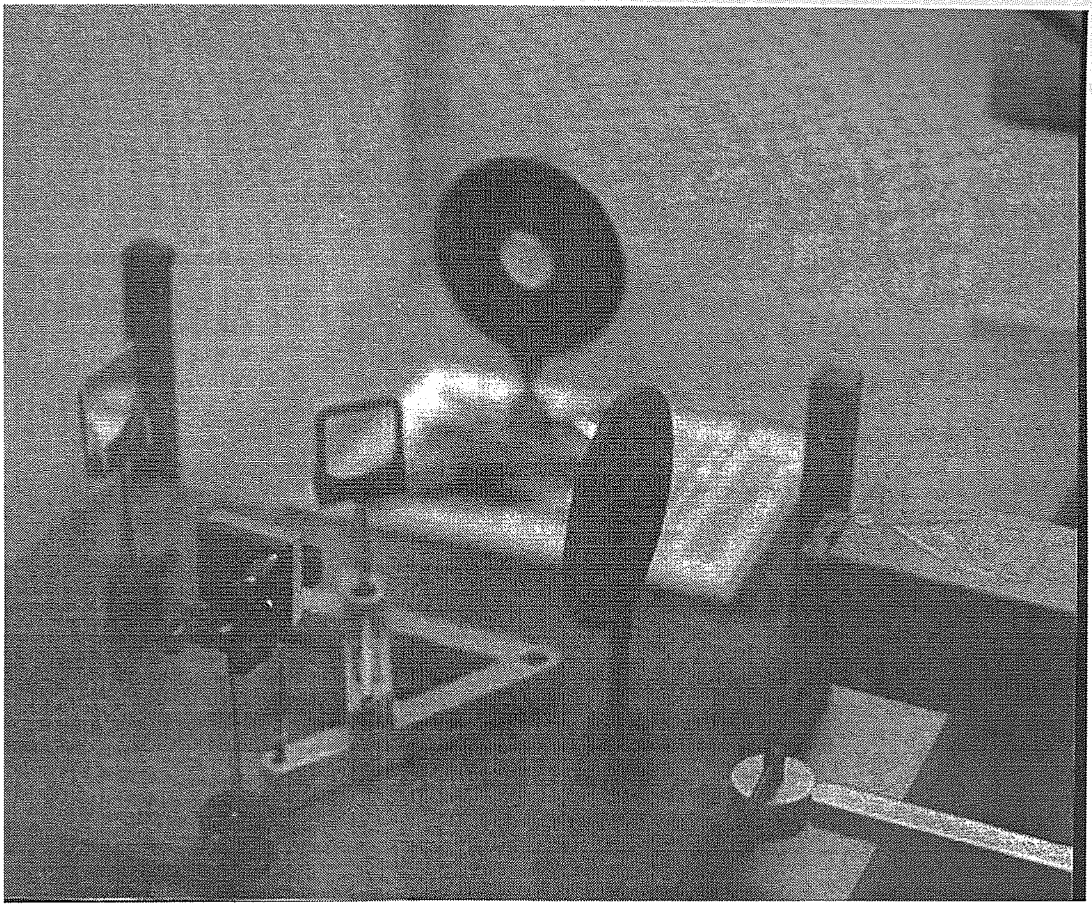


Figure 4.6. *Photograph of the lab and the modified set-up of the interferometric device (Twyman-Green interferometer).*

According to the above photo it can be seen the changes made from the first attempt.

a) A collimated lens of focal length +100 mm was placed in front of the laser at a distance equal to its first focal length. This produced the initial *"reference wave front"* which was *plane*.

b) New beam-splitter (50/50) and new flat mirrors (one fixed and the other movable in terms of three screws for directional movements) were used. This produced better optics with less aberration affecting the system.

c) The camera was placed exactly behind the semi-transparent screen at 0° angle.

After the changes were made, spherical and cylindrical trial lenses of known power were tested with the new system. Some examples of the tested lenses with the Twyman-Green interferometer are given below. Note that a complete set of photographs is given in Appendix III.

For a spherical trial lens of +1.00 Ds the fringe diameter of the 5th dark fringe was 87 mm so $x_n = 87/2 = 43.5$ mm. The magnification used to make the fringe pattern visible was 35x. So the actual fringe size was 43.5/35 = 1.24 mm. By using the equation $R = x_n^2 / n\lambda$ then R = 488,20 mm = 0.488 m^{-1}. $F_{lens} = 1/R = 2.048$. But due to the double pass of the beam from the tested lens the wave front power is doubled. So $F_{real} = 1.02$

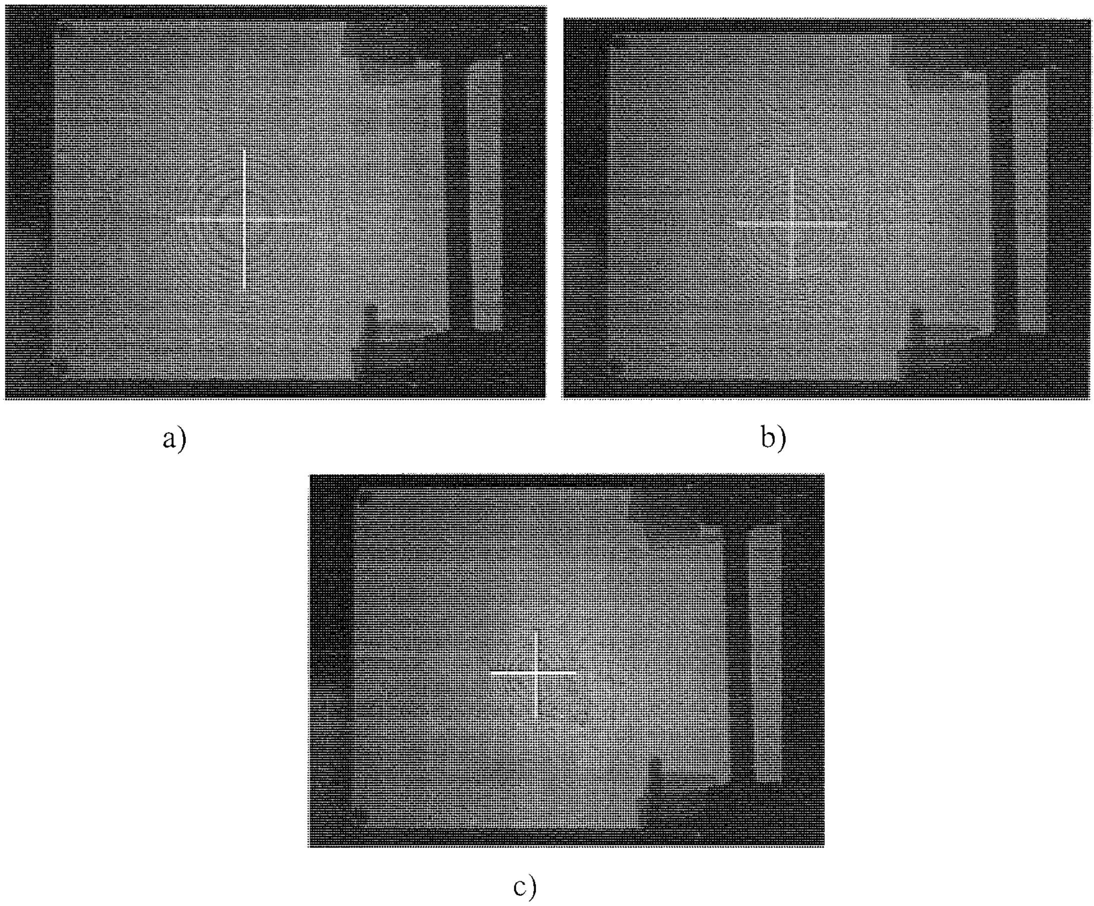


Figure 4.7. *Fringe patterns of trial lenses tested with a) +1.00 Ds power b) +2.00 Ds power c) +3.00 Ds power.*

Table 4.2. shows the results with the new set-up (Twyman-Green interferometer) for spherical and cylindrical trial lenses of known power.

Table 4.1b

Lens type.	*Distance 5^{th} fringe (x) axis.*	*Distance (y) axis.*	*F1*	*F2*
-1.00 Ds	83	83	*1.125*	*1.125*
+1.00 Ds	87	87	*1.024*	*1.024*
- 2.00 Ds	61	61	*2.153*	*2.153*
+2.00 Ds	60	60	*2.083*	*2.083*
- 3.00 Ds	51	51	*2.980*	*2.980*
+3.00 Ds	50	50	*3.100*	*3.100*
- 4.00 Ds	44	44	*4.004*	*4.004*
+4.00 Ds	43	43	*4.192*	*4.192*
- 0.50 Ds	120	120	*0.538*	*0.538*

Dimensions of fringe pattern from photographs (mm). F1 and F2 represent equivalent maximum and minimum calculated powers (D).

From the above table it is obvious that with such an experimental set-up the results taken were very near to the nominal power of the trial lenses tested. It should be mentioned that only the *absolute power* could be measured and it is not possible to know if the lens is positive or negative. According to *Twyman (1988)* the resulting power is the combination of both surfaces of the lens tested. In order to check the repeatability of the method, the lenses were measured 3 times using this system. The statistical analysis of the results for the proposed method compared to Auto-focimeter readings is given below.The statistical analysis is for the measurement of spherical trial lenses. Each lens was measured three times with an Auto-focimeter (TOMEY TL-100) and three times with the interferometric technique described in this chapter. The results are given in the table 4.2 below.

Table 4.2 SPHERICAL LENSES

Lens nominal powers (D)	
+1.00	*-1.00*
+2.00	*-2.00*
+3.00	*-3.00*

Measurements

Auto-focimeter (D)	**Interferometry (D)**
+1.01	+1.02
+1.02	+1.14
+1.00	+1.09
+1.96	+2.08
+1.95	+2.12
+1.95	+2.14
+2.96	+3.10
+2.97	+3.03
+2.96	+3.15
-1.00	-1.01
-1.01	-1.12
-1.02	-1.07
-1.97	-2.15
-1.98	-2.09
-1.97	-2.11
-2.98	-2.98
-2.97	-2.95
-2.98	-3.04

Auto Focimeter Mean	Interferometry mean
+1.01	+1.08
+1.95	+2.11
+2.96	+3.09
-1.01	-1.07
-1.97	-2.12
-2.98	-2.99

Comparison of spherical lens powers measured with auto-focimeter and interferometry

Statistics for the spherical lenses measured utilizing their average results (Each lens was measured three times)

In order to compare the two measuring methods the 'difference versus mean plot' is used *(Bland & Altman. 1986.1999).* With this method the differences between the two measuring methods are plotted against the averages of the two methods.

DIFFERENCE VERSUS MEAN PLOT – SPHERICAL LENSES

Method A : Auto_focimeter
Method B : Interferometry

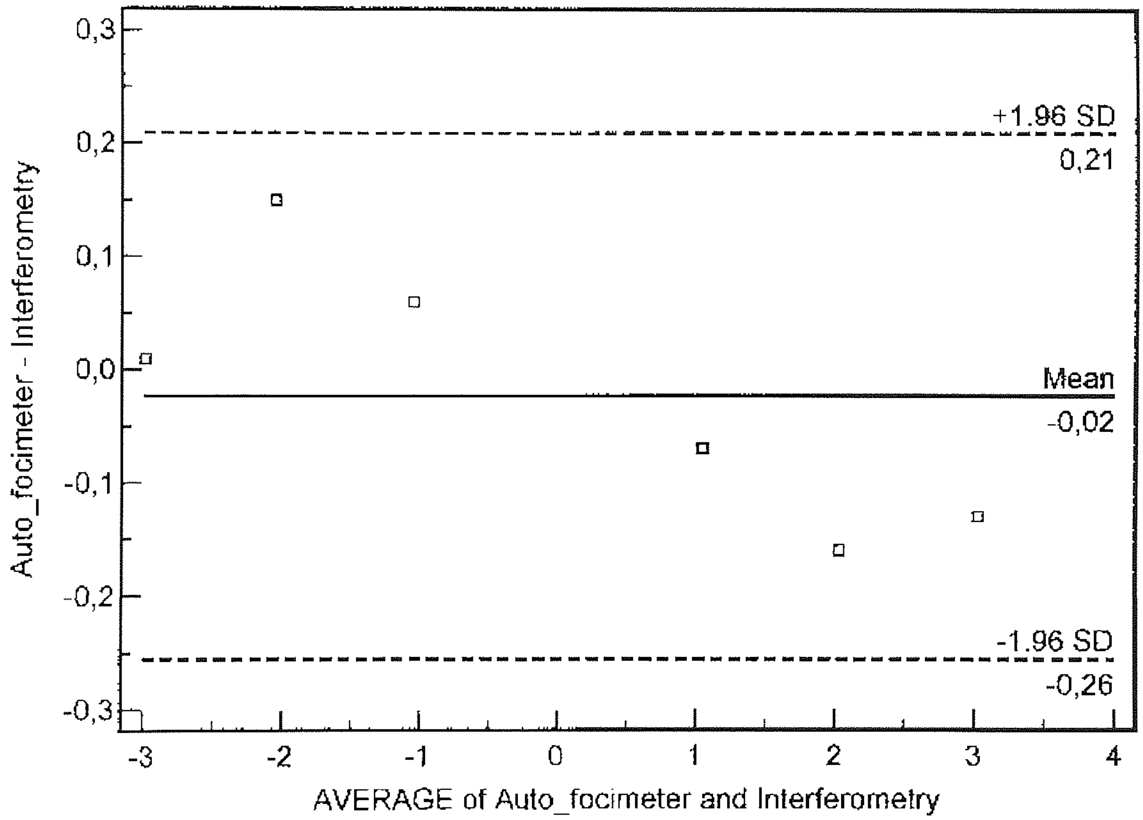


Figure 4.8. *Difference versus mean plot where "Interferometer" and "Auto-focimeter" are the two measuring methods that are compared.*

Using the paired 't' test, there was no significant difference between the two measurement methods at the 95% level (p = 0.65). The limits of agreement were ±0.24 DS.

Table 4.3. ***CYLINDRICAL LENSES***

Lens nominal powers (D)

+1.00 cyl	*-1.00 cyl*
+2.00 cyl	*-2.00 cyl*
+3.00 cyl	*-3.00 cyl*

AF A°cyl	INT A°cyl	AF A°+90°cyl	INT A°+90°cyl	AF CYL	INT CYL
0.02	0.12	0.97	1.01	0.95	0.89
0.01	0.08	0.96	1.15	0.95	1.07
0.01	0.10	0.98	1.12	0.97	1.02
0.06	0.17	2.06	2.07	2.00	1.90
0.07	0.15	2.05	2.15	1.98	2.00
0.06	0.14	2.06	2.16	2.00	2.02
0.04	0.15	3.03	3.11	2.99	2.96
0.04	0.18	3.04	3.10	3.00	2.92
0.04	0.14	3.04	3.14	3.00	3.00
-0.04	-0.11	-0.94	-1.05	-0.90	-0.94
-0.05	-0.13	-0.95	-1.11	-0.90	-0.98
-0.05	-0.17	-0.95	-1.16	-0.90	-0.99
-0.02	-0.15	-1.96	-2.14	-1.94	-1.99
-0.03	-0.08	-1.97	-2.17	-1.94	-2.09
-0.03	-0.11	-1.97	-2.10	-1.94	-1.99
-0.04	-0.14	-2.97	-2.91	-2.93	-2.77
-0.06	-0.12	-2.97	-2.95	-2.91	-2.83
-0.05	-0.18	-2.98	-3.08	-2.93	-2.90

Axis meridian means		Cyl meridian means		Cyl power means	
AF	INT	AF	INT	AF	INT
0.01	0.10	0.97	1.09	0.96	0.99
0.06	0.15	2.06	2.13	2.00	1.98
0.04	0.16	3.04	3.12	3.00	2.96
-0.05	-0.14	-0.95	-1.11	-0.90	-0.97
-0.03	-0.11	-1.97	-2.14	-1.94	-2.03
-0.05	-0.15	-2.97	-2.98	-2.92	-2.83

Cylindrical lenses measured with auto-focimeter (AF) and interferometry (INT) in the axis meridian (A°) and power meridian (A°+ 90°)

DIFFERENCE VERSUS MEAN PLOT– CYLINDRICAL LENSES

Method A : Auto_focimeter
Method B : Interferometry

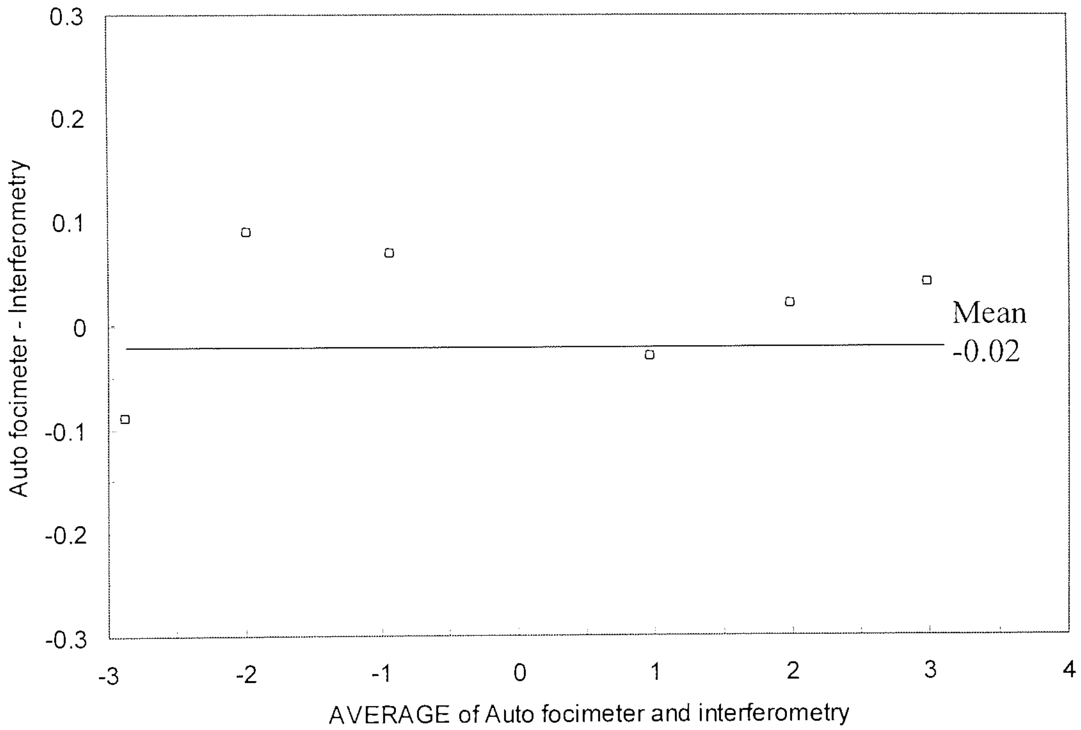


Figure 4.9. *Difference versus mean plot where "Interferometer" and "Auto-focimeter" are the two measuring methods that are compared for the results on the power difference of the two principle meridians of the cylindrical lenses*

Using the paired 't' test, there was no significant difference between the two measurement methods at the 95% level ($p = 0.48$). The limits of agreement were ±0.13 DC. The apparent improvement in agreement for the cylindrical lens measurement compared with the spheres could be due to the fact that two measurements were taken for the cylindrical lenses to determine the maximum and minimum powers. It is likely that the nominally spherical lenses also had some cylindrical power, and if this was considered then an improved correlation might be achieved.

All the above statistics were carried out using the statistical computer software known as *"Medcalc"*.

Summary

A new method is provided for measuring the power of ophthalmic lenses and this alternative method is based on interferometry. More specifically a Twyman-Green interferometer was set to measure trial lenses of known power. The fringe patterns were photographed and then the power of the wave front produced due to the insertion in the set-up of the trial ophthalmic lens was measured. This is equal to the power of the trial lens. The fringes were tested compared to the plano reference wave front produced when the system did not have any lens inserted.

The results were compared with the results taken by measuring the lenses with an Auto-focimeter. A statistical analysis of the results comparing the two methods was made using the Bland an Altman statistical method. From the statistics, and especially the p-value (p should be in all cases $p > 0.05$), it showed that the two measuring techniques do not different significantly. Also, from the difference versus mean plot it shows that there is a maximum difference of about 0.24 D between the two methods for both spherical and cylindrical lenses. Having that in mind the above mentioned experimental set-up is used to measure complicated lenses like progressive addition lenses and this was the first time that such an experiment has been carried out.

Chapter 5.

Measurements of PALs with interferometry

Introduction

Progressive Addition Lenses (PALs) are very complicated as ophthalmic lenses. Due to the fact that there are no borders visible for far, intermediate and near vision areas on the lens surface, these lenses are difficult to measure and to access their performance. So far the method most commonly used for measuring these lenses is the use of Auto-focimetry.

A more precise method is used such interferometry (Twyman-Green interferometer) in providing information about the power distribution on the Pal's surface. It is well known that so far the performance of such complex lenses is presented by providing contour plots of the power distribution on the lens surface and the unwanted astigmatism distribution that these lenses present outside the progressive corridor. The same way of performance presentation is used only the data is extracted by using the interferometric method proposed in Chapter 4. Such a technique has never so far been used to provide the necessary information for evaluating such lenses. This innovating approach can be used also in the manufacturing sector of these lenses in order to provide the manufacturer data on the surface of the lenses without the need of subjective observations.

Measurements of Pals

At first, the initial idea was to get only one fringe pattern of the whole surface performance. Using a beam expander after the collimating lens in front of the laser, which produces the parallel wave front, this could be achieved. The beam expander is an optical element that provides a large width of the initial parallel wave front but still leaving the wave front parallel .

Unfortunately the fringe pattern produced was highly irregular and almost impossible to interpret. The performance of progressive addition lenses is assessed with contour plots showing the power and the unwanted astigmatism distribution on the lens surface. By having only one fringe pattern for the whole lens it was also impossible to have the same presentation on their performance by using the interferometric technique. So it was decided to have multiple measurements on the PAL surface. These measurements were tried to resemble the measurements taken with an Auto-focimeter so it would be possible to compare the results of each method. The set-up used was the same as the one described in Chapter 4. and instead of trial lenses progressive addition lenses were placed into the system.

Progressive addition lenses were introduced in the system and measured at 15 points. The lenses were measured at points, which are 10 mm apart horizontally. Figure 5.1. shows on a progressive addition lens surface the points, which were measured.

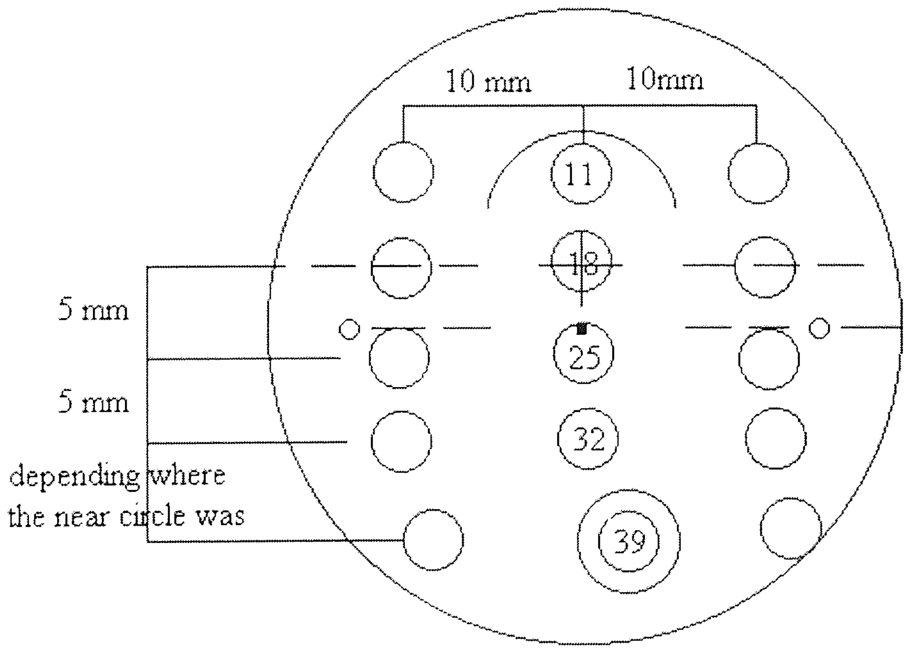
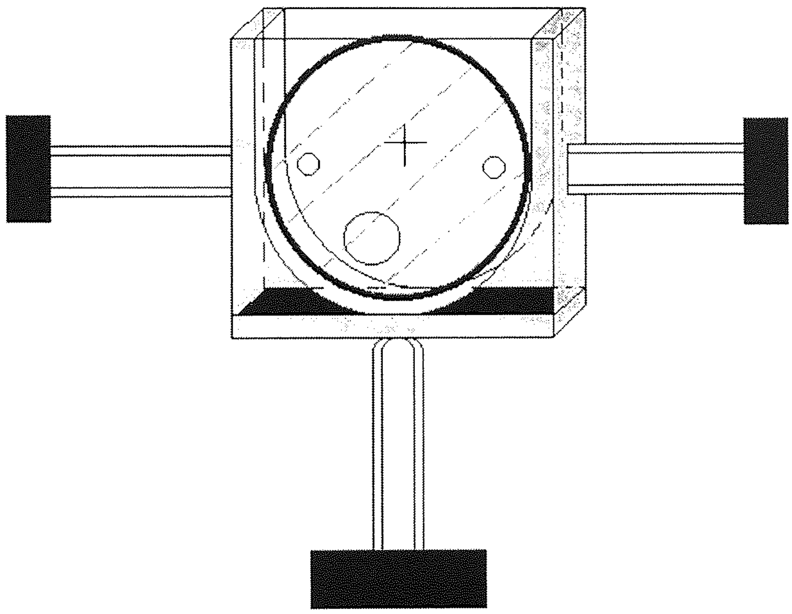


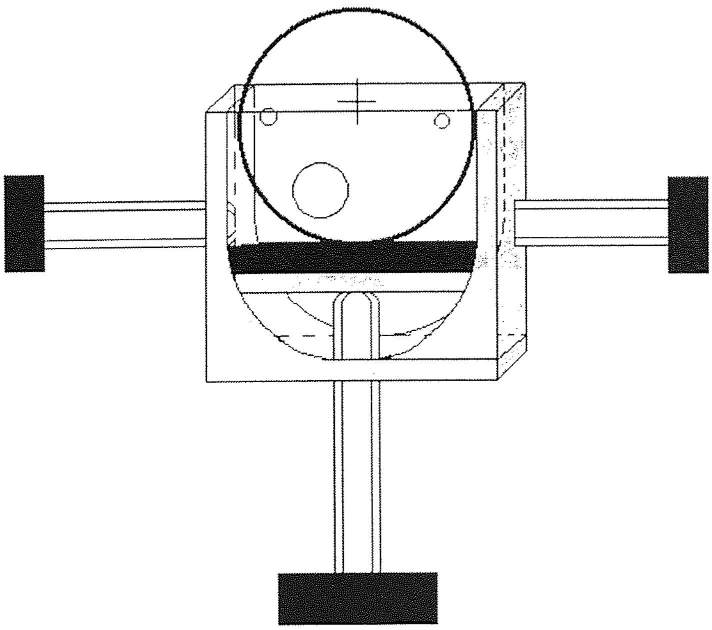
Figure 5.1. *Points (circles) on a progressive addition lens where measurements with interferometry took place. Each circle is 2,5 mm in diameter*

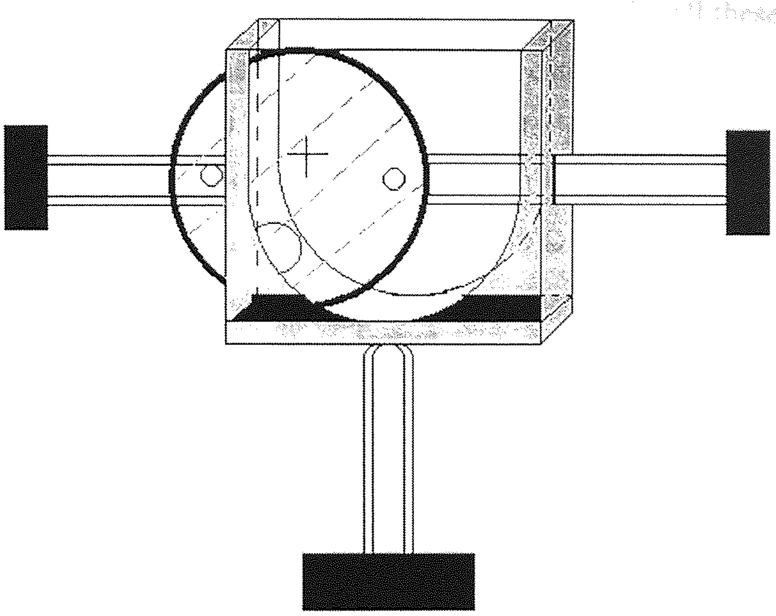
Point 11 represents the semi-circle indicating where the distance power and axis should be checked. Point 18 represents the fitting cross which is normally located at the patient's pupil. Point 39 represents the circle indicating where the centre of the reading area is. The produced fringes where photographed, measured and the resulting dioptric power was calculated for each point. The plotting for the spherical and the cylindrical component is given in terms of spherical power and unwanted astigmatism distribution. Each progressive lens was clipped on a stand with verniers horizontally and vertically, in order to ensure that the correct point was measured each time. Figure 5.2. shows the stand that was used to hold the progressive addition lenses, in order to provide movement along the lens surface horizontally and vertically.



(A)

(B)





(C)

Figure 5.2. *Shows the holder stand (a) for precisely moving progressive addition lenses, in order to take measurements every 5 mm horizontally (c) and vertically (b) on the lens surface.*

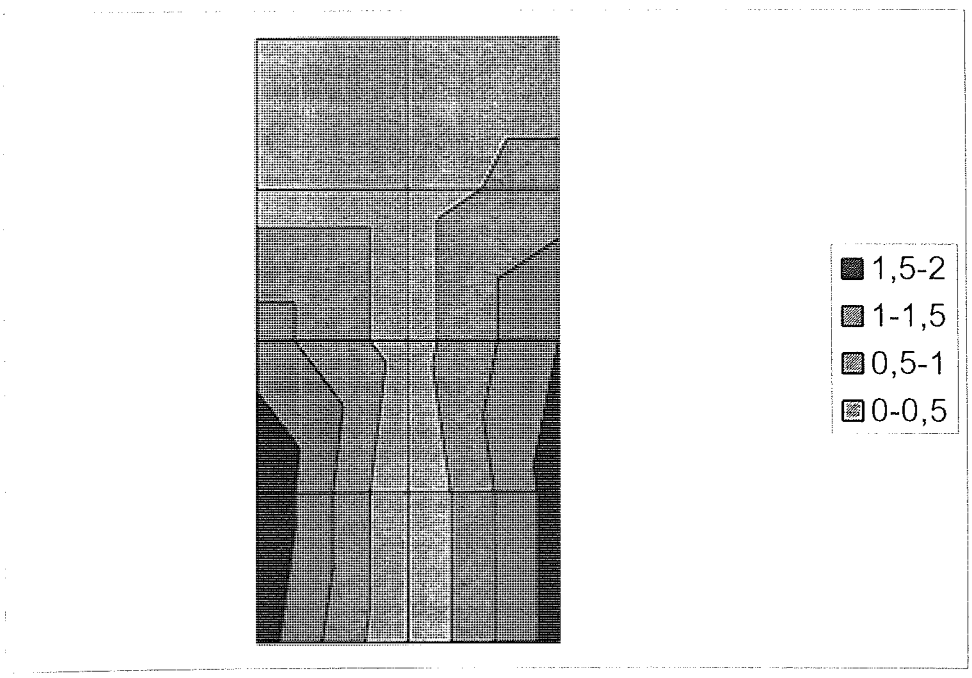
Each of the progressive addition lenses was measured at 15 points, as it was mentioned before. Each point was treated as though it was a spherical or cylindrical lens. These points were selected to cover most of the usable area of the lens. This area represents the main part of the progression corridor the distance and near vision measuring point the fitting cross and an area 10 mm outside of the progressive corridor revealing the disadvantage that such lenses have such unwanted astigmatism. By having each point measured then we could plot the usable area in terms of power distribution.

The progressive addition lenses selected for the research were taken from the Greek market representing companies' products, which are widely used nowadays. From Essilor it was selected to measure *Comfort* and the new lens design under the trademark *Panamic*. From the company Hoya the lenses *GP* and Summit *Pro* lens designs were selected. From Aoptical the lenses selected were *AO Pro* and the *Compact*. From Zeiss the *Gradal HS*, Rodenstock *Progressiv S* and from Nikon

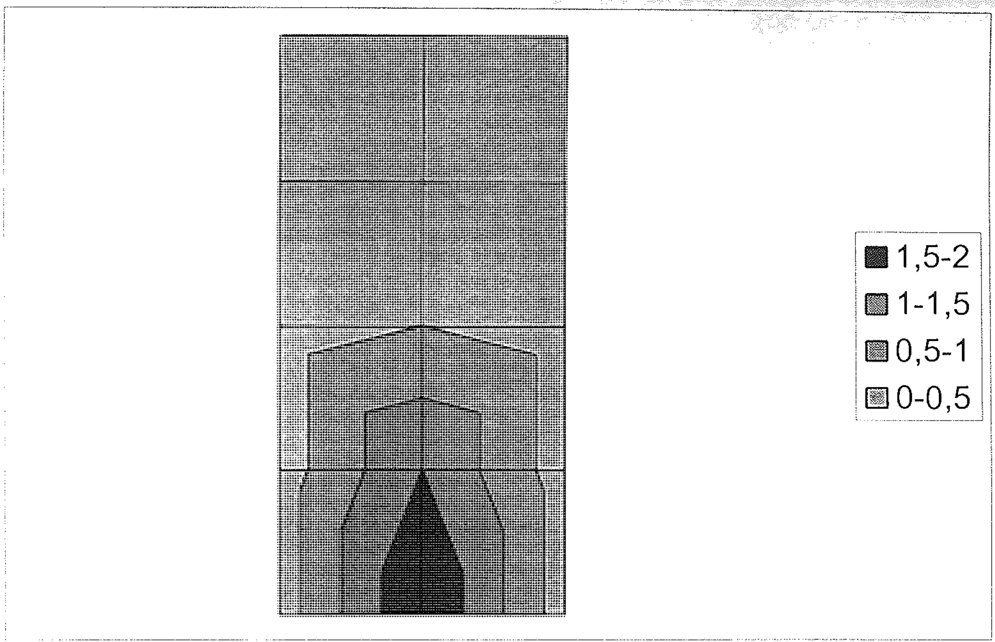
Presio were selected. These 9 lens designs represent the majority of the progressive lenses marketed in Greece at the time of this research. All these lens design are very similar to each other belonging to the major category of *ultra soft* designs. The only different one is the *AO Compact* which is a design produced to fit in small frames (B vertical dimension of the frame B< 35 mm). All the lenses were measured having plano distance vision zone and addition 2.00 D which represents the mean value of additions used from presbyopic wearers.

In addition, all the above mentioned lenses were measured with an Auto-focimeter (Tomey) at the same points in order to compare the two methods in their results of measuring such complex lenses. With the Auto-focimeter besides the same 15 points measured, other 34 points were measured in order to have a complete presentation of the power distribution and the performance of these lenses. So there was a total of 49 points measured on the surface of such lenses covering all the area representing a viewing angle of 35°.

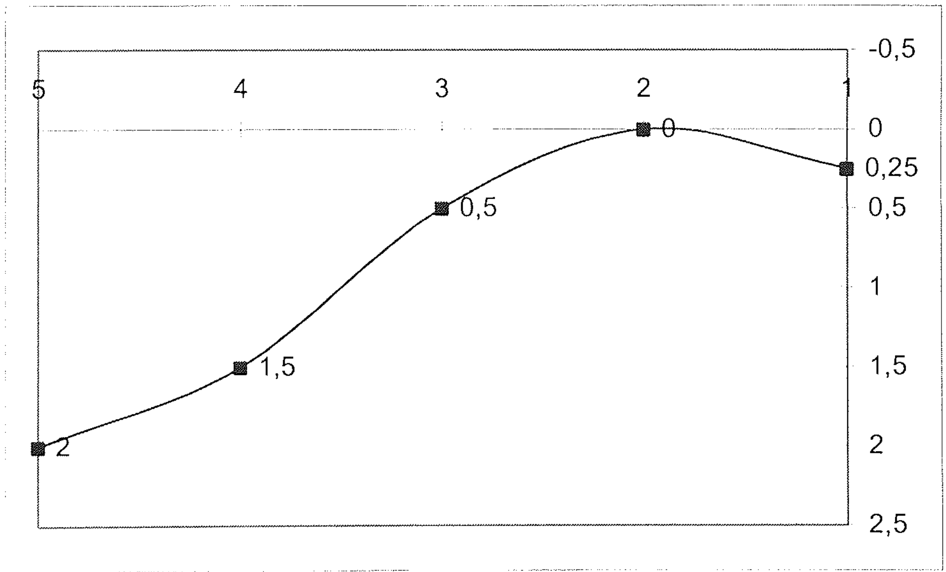
The results are given for one of the above-mentioned lenses in the following plots. The results of the rest lenses are presented in Appendix IV.



a)



b)

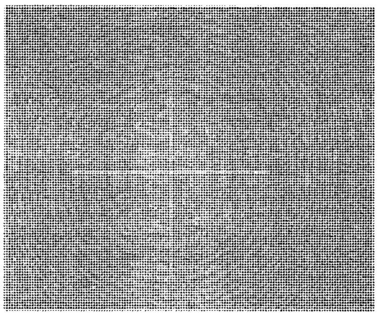


c)

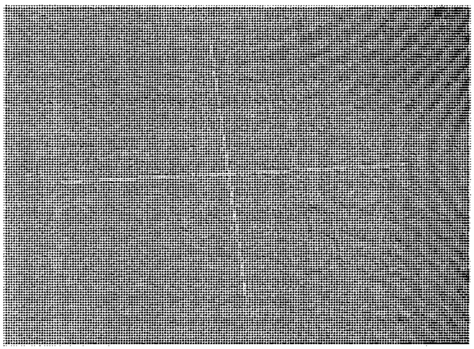
1	Far (point 11)
2	Cross (point 18)
3	5 mm below cross (point 25)
4	10 mm below cross (point 32)
5	Near vision circle (point 39)

Figure 5.3. *a) Diagram showing the distribution of the unwanted astigmatism presented by the lens b) diagram showing the spherical power distribution c) plot of the power progression at the progression corridor. All the above results are for Hoya GP plano/add 2.00 D. Measurements taken with interferometry.*

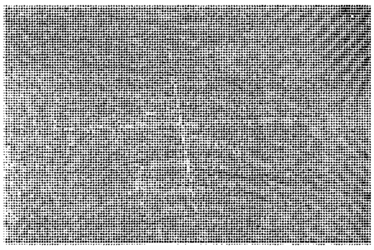
The photographs of the fringes taken for Hoya GP at the progression corridor are given below



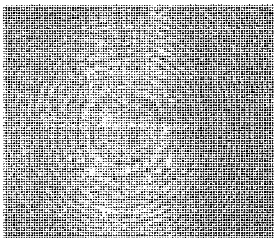
0,25 Ds at point 11



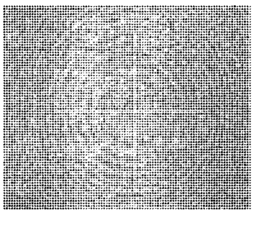
plano/0,25 Dc at point 18



0,50 Dc/0,75 Dc → 0,50Ds/0,25Dc at point 25



1,50 Ds at point 32



2,00 Ds at point 39

For comparison the same lens was measured with the Auto-focimeter but this time the points were 49 on the lens surface. These points are seen in the following figure.

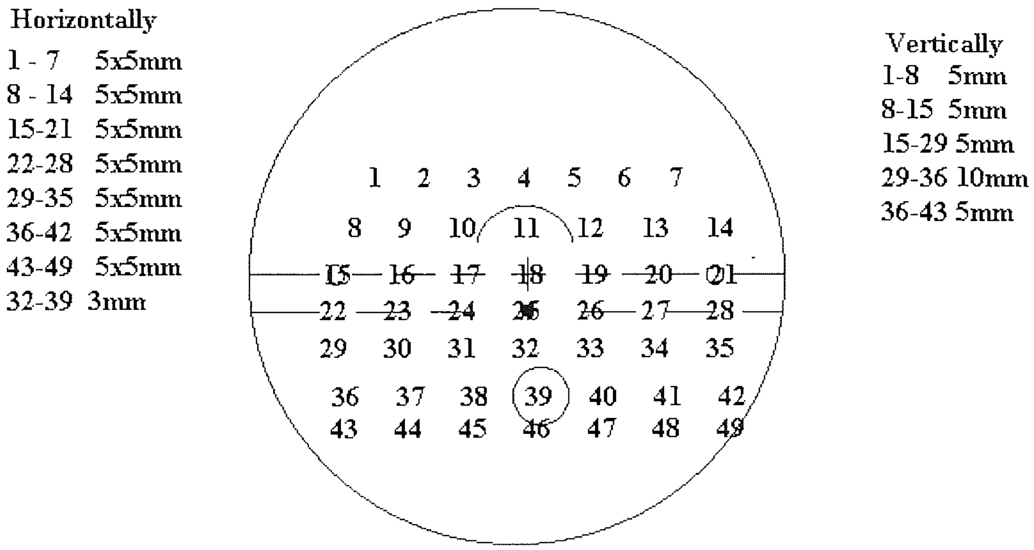
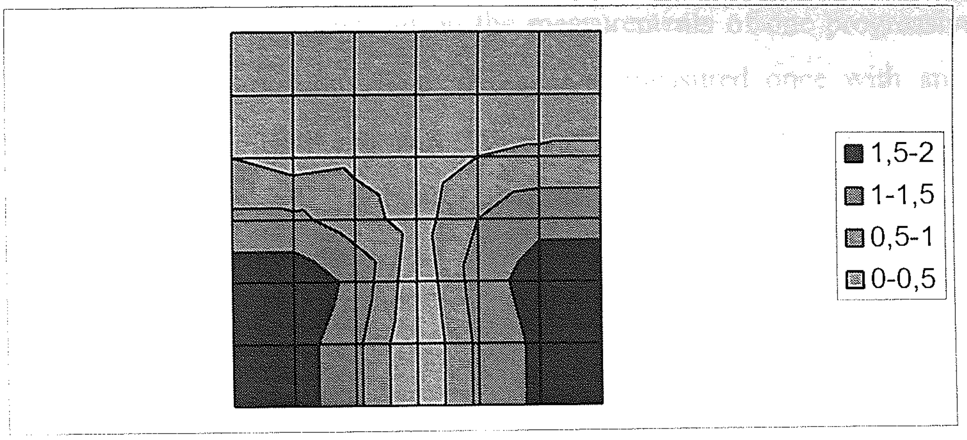
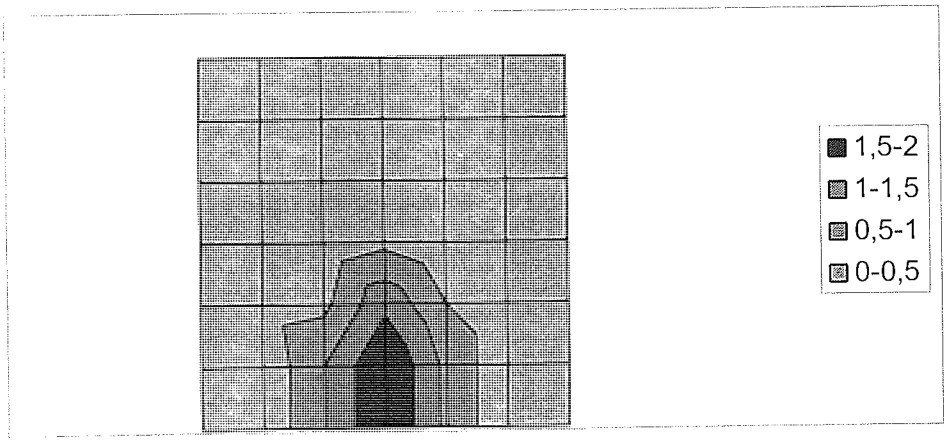


Figure 5.4. *Points on a progressive addition lens where measurements with an auto-focimeter took place.*

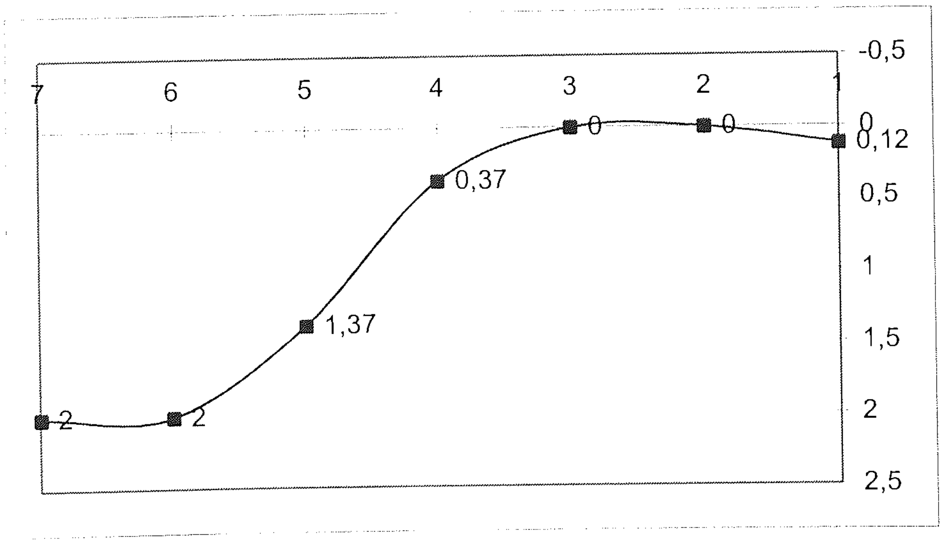
Figure 5.5 shows the results taken with an auto-focimeter for comparison with the results taken with interferometry. The results for both interferometric technique and auto-focimeter are presented for all lenses tested in Appendix IV.



a)



b)



c)

Figure 5.5. *a) Diagram showing the distribution of the unwanted astigmatism presented by the lens b) diagram showing the spherical power distribution c) plot of the power progression at the progression corridor. All the above results are for Hoya GP plano/add 2.00 D. Measurements taken with auto-focimeter.*

The statistical analysis is carried out on the measurements of one progressive lens (Hoya GP) at the lens corridor. The lenses were measured once with an Autofocimeter (TOMEY TL-100) and with the interferometric technique described in chapter 4. The results are given in the table below.

Table 5.1.

Points of measurement	Autofocimeter		Interferometry	
	sph	cyl	sph	cyl
Point 11	0	0	0.25	0
Point 18	0	0.12	0	0.25
Point 25	0.37	0.25	0.50	0.25
Point 32	1.37	0.12	1.50	0
Point 39	2.00	0	2.00	0

Spherical component

DIFFERENCE VERSUS MEAN PLOT

Method A : Autofocimeter
Method B : Interferometry

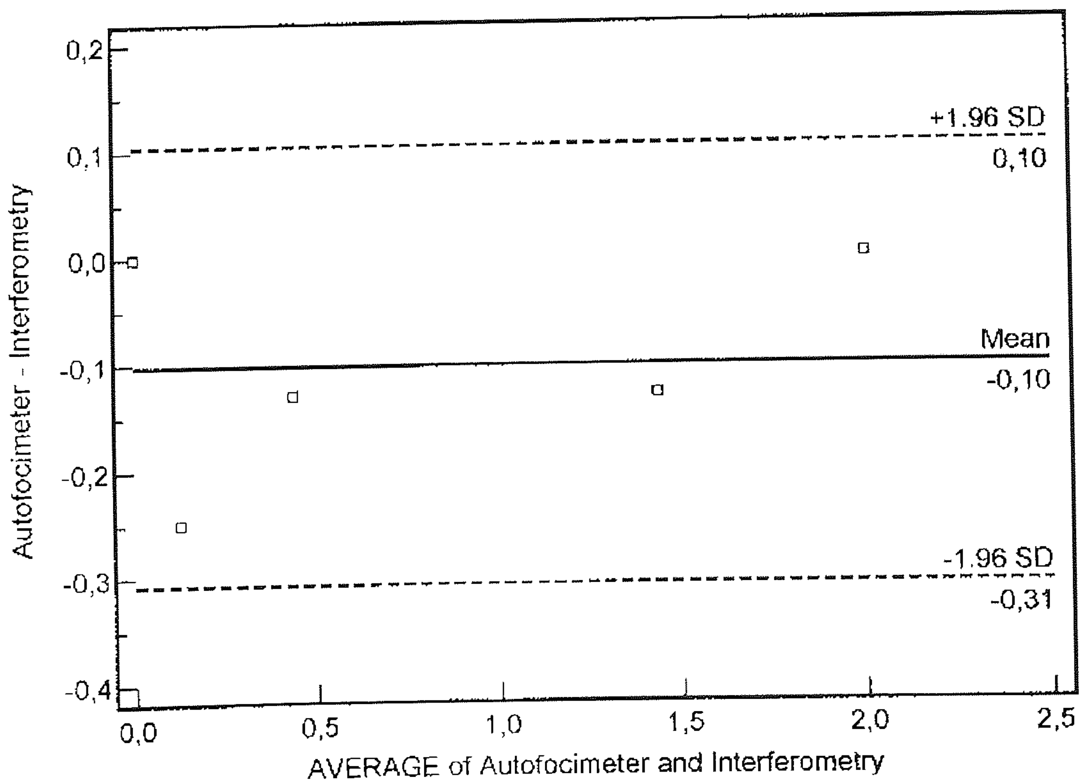


Figure 5.6. *Difference versus mean plot where "Interferometer" and "Autofocimeter" are the two measuring methods that are compared for the results on progressive addition lenses and more specifically on the spherical component.*

The mean difference between the methods when measuring spherical components on progressive lenses was not statistically different at the 95% level (paired sample 't' test p = 0.10) with a limit of agreement of ±0.20 DS.

Cylindrical component

DIFFERENCE VERSUS MEAN PLOT

Method A : Autofocimeter
Method B : Interferometry

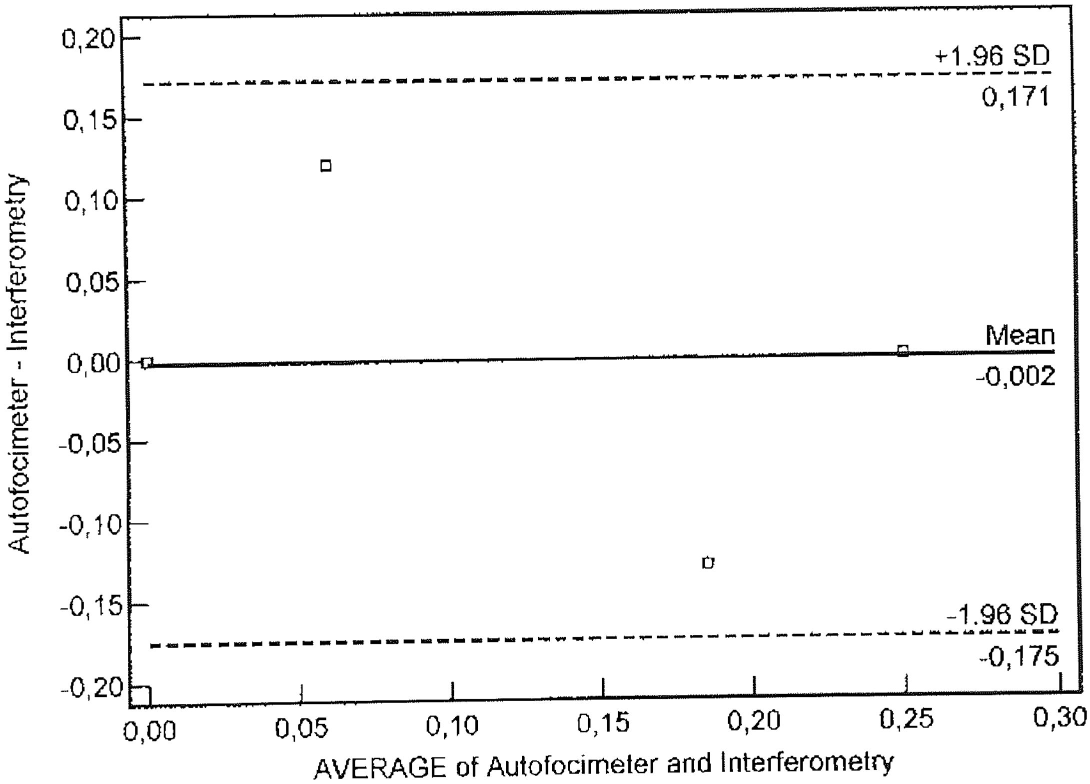


Figure 5.7. *Difference versus mean plot where "Interferometer" and "Autofocimeter" are the two measuring methods that are compared for the results on progressive addition lenses and more specifically on the cylindrical component.*

The mean difference between the methods when measuring cylindrical components on progressive lenses was not statistically different at the 95% level (paired sample 't' test p = 0.96) with a limit of agreement of ±0.17 DC.

Summary

A Twyman-Green interferometer was utilized to take measurements on progressive addition lenses. At first the fringe pattern of the whole lens was taken in order to assess the performance of these lenses. But due to the fact that from the pattern it was impossible to interpret the lens data, specific points on the lens surface were then measured and the power of these points was calculated from the fringe pattern being photographed.

The results were presented in the customary way for the presentation of progressive addition lenses performance. Using contour plots, the power and the unwanted astigmatism distribution is presented. The measuring points on the lens surface contained the progressive corridor, the far and near vision points, and points 10mm away from the corridor (15 points in total). These results were compared with measurements taken with an Auto-focimeter (49 points in total) and contour plots again were presented for power and astigmatism distribution. The plotting for both measuring techniques were very similar, although the measuring points were not numerically the same. From the statistics and especially the p-value (p should be in all cases $p > 0,05$) showed that the two measuring techniques do not different significantly. Also from the difference versus mean plot it shows that there is a difference of about 0.20 DS for the spherical component while it was about 0.17 DC for the cylindrical component between the two methods.

BS 2738 Part 1 (1998) gives tolerances for the measurement of spectacle lenses, including progressive addition lenses. Within the power range of ±3.00 D there is a tolerance of ±0.12 D. Thus this measurement method would not satisfy the requirements of checking glazed spectacle lenses, but it could be used to build up a power contour map of the lens power distribution. Such a plot can be useful in giving a qualitative analysis of a lens design.

With interferometry it was difficult and time consuming to get as many measurements as those taken with the Auto-focimeter due to the manual and laborious nature of the technique. The technique can be improved in order of the time needed if the fringe pattern can be analyzed by a computer with the appropriate software.

Chapter 6.

Discussion - Conclusion

Progressive addition power lenses (varifocals) became commercially available to help presbyopes in the 1960s with the production of the Varilux I by Essel in France (Maitenaz, 1966).

Many requirements are imposed on a universally usable multifocal lens, thus: the far-vision zone should have spherical and astigmatic deviations as low as possible for the spectacle wearer because the highest possible visual acuity is required for viewing into the distance. On the other hand, the near-vision zone should be adequately high so that no great unnatural drop in viewing direction is needed for near vision viewing and the usable region of the multifocal lens should be adequately wide.

The region in the progression zone at both sides of the principal viewing line, in which clear viewing is possible, is known as progression channel. The wearer of the spectacles desires that this progression channel should be as wide as possible in order not to be compelled to move the head when viewing objects at mid-distances. The acceptance of every multifocal lens is essentially dependent upon this width.

Requirements with respect to binocular viewing are in addition to the above monocular requirements. If one targets the optimal correction of the spectacle wearer, then the binocular characteristics of the lens deserve special attention.

Binocular viewing arises from the co-action of the eye pair. Binocular spectacle lens characteristics are therefore characteristics of the lens pair. The requirement for binocular balance for the eye pair requires the equivalence of the lens pair. This equivalence must be given for each viewing direction and is referred to the imaging quality and to the prismatic directional deflection.

Equivalent imaging quality makes possible the same vision right and left and equivalent prismatic directional deflection ensures undisturbed fusion when viewing an object point (in direct viewing) and for customary depth perception when observing the region around the object (in indirect viewing).

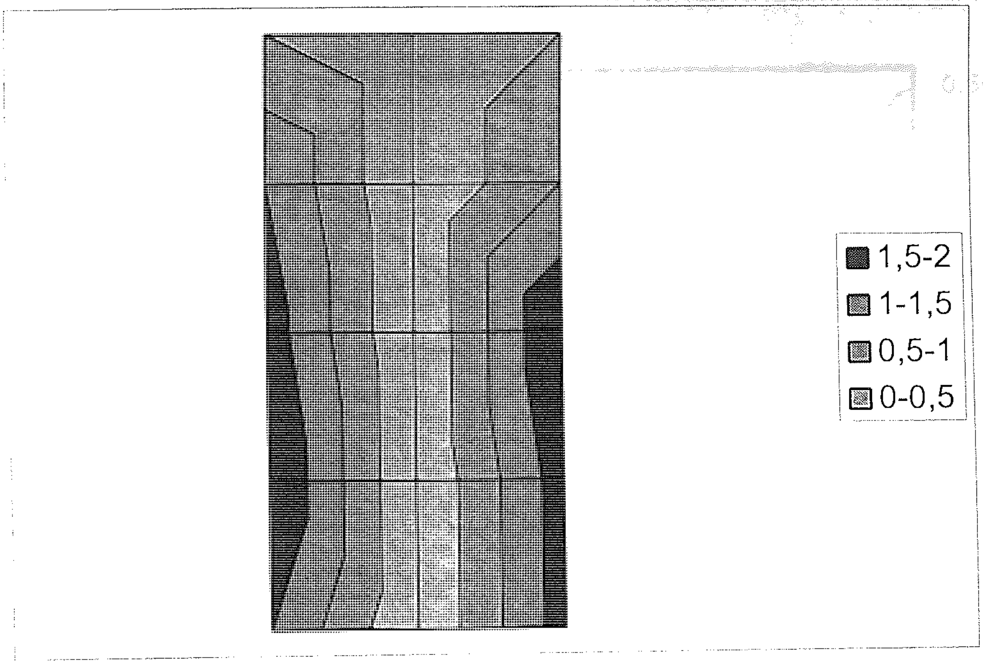
All of these monocular and binocular requirements should be satisfied as well as possible for all possible dioptric powers and for all occurring additions. A certain deficiency of all multifocal lenses is that astigmatic deviations, which prevent clear vision, are unavoidable especially in the progression zone lateral to the the principal viewing line.

Today a large number of different designs exist on the market and it is difficult to make comparisons between them. This is partly because the optical assessment of these non-rotationally symmetric aspheric lenses is not easy due to the complexity of these surfaces. Single vision lenses, bifocals and trifocals are easy to verify using standard focimeter techniques since they have clearly defined regions of uniform power

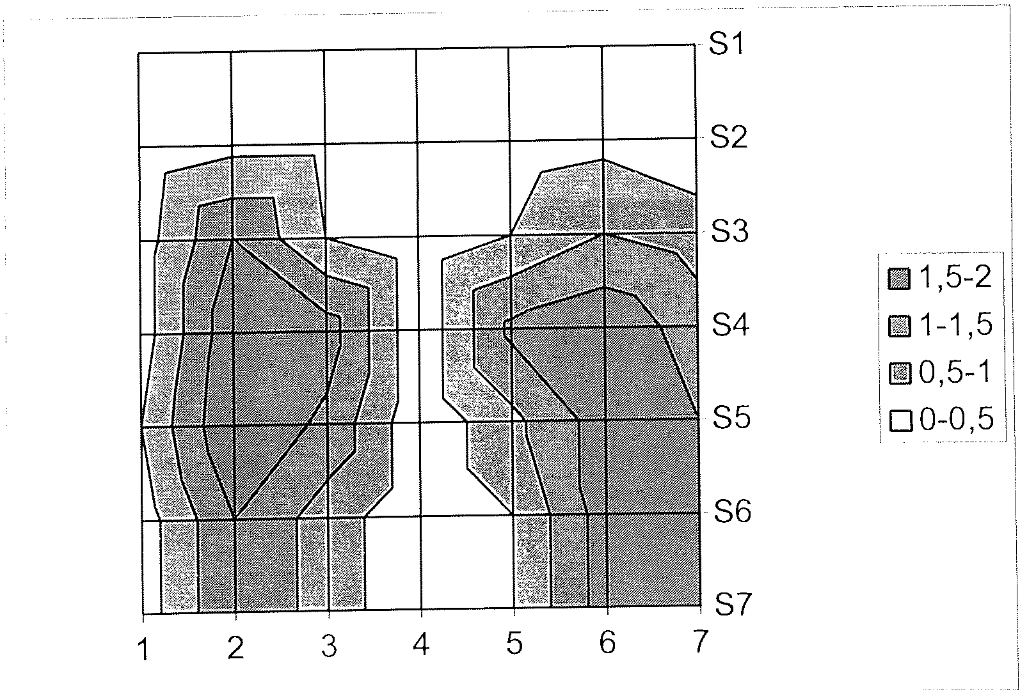
Progressive addition power lenses (PALs), by their very nature, have power that varies across their effective aperture. This is the reason that mapping of the spherical power across the surface of the lens will be sufficient to characterise its optical properties. However, the aspheric nature of a PAL leads to significant astigmatism, distortion and other aberrations particularly in the transition zones.

Many authors used multiple point focimeter techniques, which allows the measurement of mean sphere, cylinder and cylinder axis for several points across the PAL aperture (Simonet *et al.*, 1986, Sheedy *et al.*, 1987, Atchison, 1987, Fowler and Sullivan, 1988, 1989, 1990). All of these techniques are time consuming so Fowler and Sullivan automated the measurement of a PAL with an electronic focimeter and a computer in order to assess hundreds of points.

As an example, a comparison between the interferometric method the autofocimeter measurements taken in this research and the scanning focimeter technique of Fowler and Sullivan is shown in figures 6.1 and 6.2. for the same type of lens. Although the focimeter technique can obtain a finer resolution of detail, the inaccuracies of mechanically moving the lens in relation to the focimeter aperture does induce errors. The focimeter method also takes longer to produce a plot.



Interferometric measurement Plano distance Add +2.00 Maximum cylinder 1.75 D



Autofocimeter measurement Plano distance Add +2.00 Maximum cylinder 1.87 D

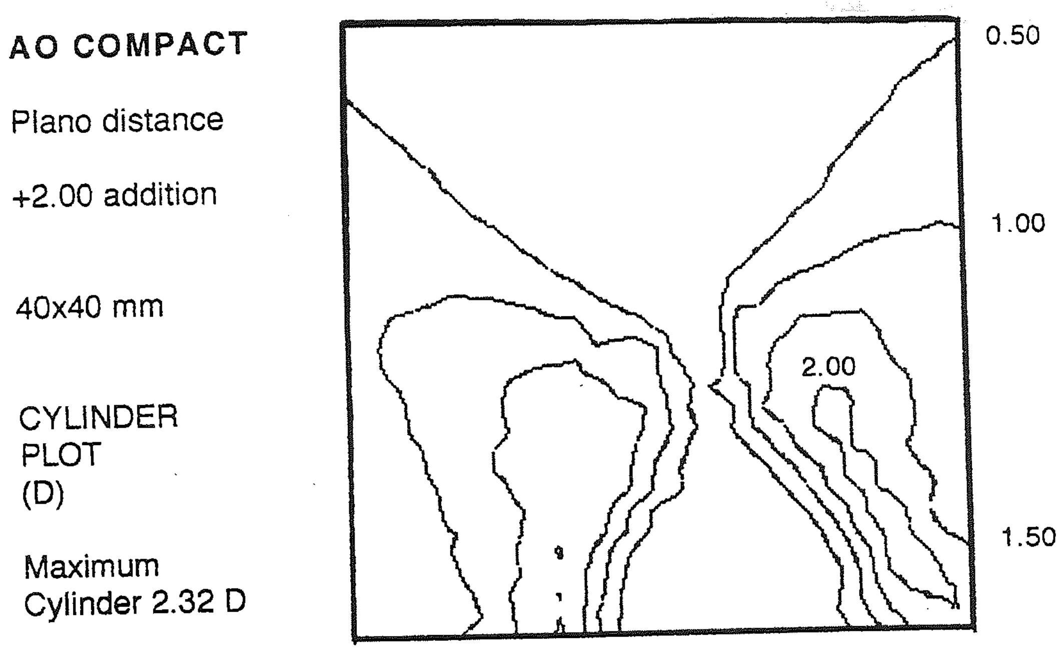
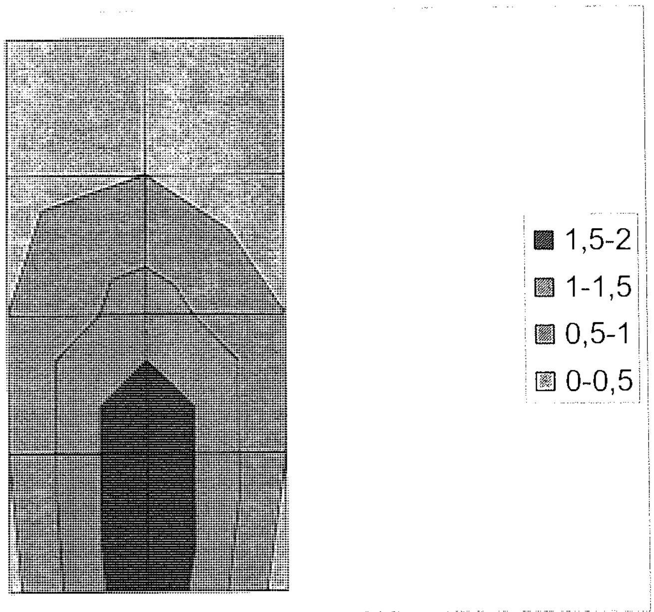
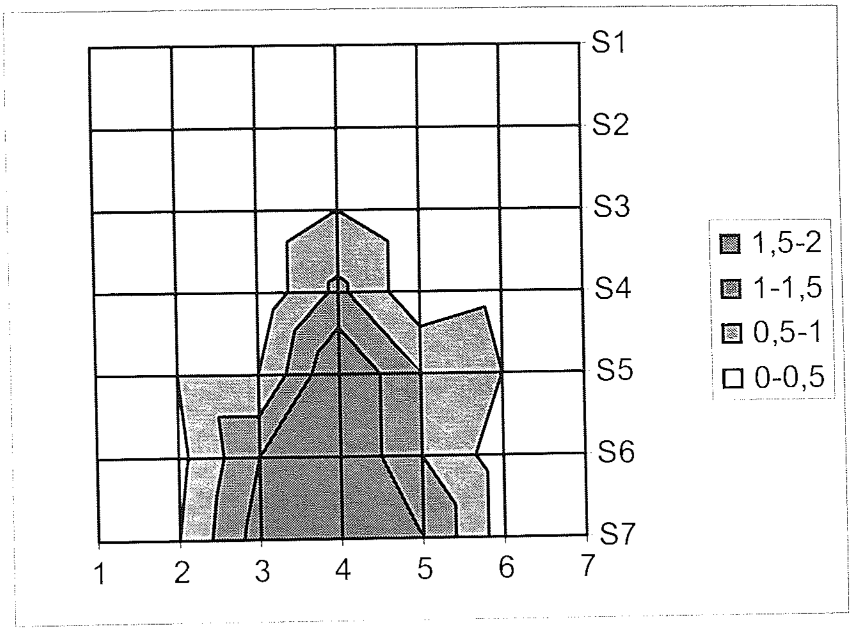


Figure 6.1.
Comparison of American Optical Compact lens measured by interferometry (top) and Autofocimeter in this research with similar lens measured by method of Fowler and Sullivan (1989) . Plots are of iso-cylinder power (D).



Interferometric measurement Plano distance Add +2.00 Maximum sphere 2.00 D



Autofocimeter measurement Plano distance Add +2.00 Maximum sphere 2.00 D

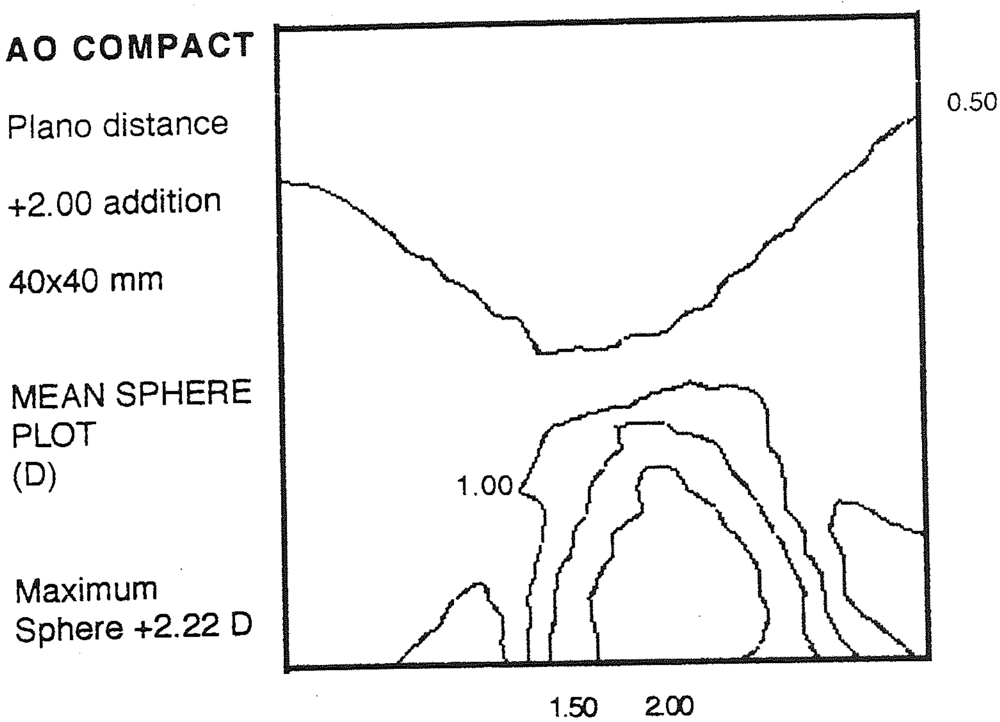


Figure 6.2
Comparison of American Optical Compact lens measured by interferometry (top) and Autofocimeter in this research with similar lens measured by method of Fowler and Sullivan (1989) . Plots are of iso-mean sphere power (D).

A review of the ability of modern measurement systems to measure the power that the wearer sees when looking through progressive power lenses has been provided by Bertrand (1998). Alternative techniques have also been described including interferometry and Moire′ methods (Mohr, 1989, Nakano *et al.*, 1990, Rosenblum *et al.*, 1992, Illueca *et al.*, 1998), beam deflection (Castellini *et al.*, 1994). All of these methods have the advantage of entire lens testing

A Moire′ system was developed by Rosenblum, (Rosenblum *et al.*, 1992), using image capture and digital image subtraction to generate Moire′ fringe patterns. However, it is possible to generate the Moire′ fringe patterns directly as has been shown by several other authors (Kafiri *et al.*, 1988, Nakano *et al.*, 1990).

More traditional optical test methods such as Newton's rings between a test plate and a lens surface (Illueca *et al.*, 1998) or Mach–Zehnder interferometry (Mohr, 1989) have also been applied.

Several authors have argued that it is necessary to map the lens power with respect to the vertex sphere (Simonet *et al.*, 1986; Atchison, 1987), although others have shown that the difference between measurements made with respect to the centre of rotation of the eye and with the lens static is small (Fowler and Sullivan, 1989).

As can be seen from the results it is possible to measure progressive addition lenses with interferometry. Interferometry as a technique has proven to be a right tool for the study of lenses generally. It provides information on the optical quality of the surfaces studied such as homogeneity of the material, finish faults during the polishing process of the lens, and refractive index anomalies within the lens.

When the interferometry system was tested with both spherical and cylindrical lenses of known power it provided results with good accuracy. From the statistics calculated for both spherical and cylindrical lenses compared with the auto-focimeter results there was a difference of about 0.24 Diopters between the two methods, while for progressive addition lenses this was a bit smallerat 0.20 Diopters. Although the statistical analysis carried out in chapters 4 & 5 indicate that both techniques were in reasonable agreement, these analyses should be treated with due caution given the limited sample of ophthalmic lenses measured.

Interferometry also provides information about the prismatic effect of ophthalmic lenses, and especially for astigmatic lenses it shows good accuracy for the axis direction. However it is important to emphasise that the astigmatism measured is not the oblique astigmatism that is seen by the user as this depends upon the position of the pupil.

For the measurement of progressive addition lenses, it is not possible to measure the whole lens at once, because the fringes taken when the whole lens was tested with interferometry were difficult to interpret. The fringe pattern taken was too complicated to understand and provide results as accurate as with the point measurement method. So each lens was measured at 15 points within their effective area. Although the points measured with autofocimeter were more (49 points) with the simple set-up used in this thesis and the technology used it was very time consuming to measure so many points in the progressive surface. So it was only the progressive corridor and the area 10 mm away from it that was checked with the simple Twyman-Green interferometer. Also, due to the simple technology used and due to the fact that progressive addition lenses are much more complicated than single vision lenses, the lenses chosen to be measured were checked with interferometry only. But the results taken give credit to such a very simple technology method.

Interferometry so far has been successfully employed to surface measurements, and contouring of different components and structures. The main handicap associated with interferometry is the stringent stability required of the operational environment. The extraordinary high interferometric sensitivity to displacement imposes a limitation that the components under investigation and the surrounding environment must be extremely stable. Although the breathing of the fringes always exists, it can be controlled, making the interferometric table more stable by increasing its weight with a granite plate.

This is further complicated by the fact that the recording time of the fringe patterns is a function of this sensitivity. The required exposure time is usually in the order of seconds or tens of seconds for the fringe patterns and the use of a digital camera is the most appropriate for such a technique. The plotting of the whole surface, in isospherical and isocylindrical lines, can give the surface topography of the lens according to the power distribution of the whole effective surface. The photographs in this research were taken with a manual camera and were scanned and measured with a computer. It should be mentioned that no computer software was used to interpret the fringe pattern so the results depend on the operator of the set-up and how accurate he can be in measuring the distances of the fringes from the centre of the fringe pattern.

Perhaps the traditional time consuming photographic film recording, if it is replaced by a video camera will help, consequently the experimental results to be accessed in real-time. The combination of laser, video techniques and electronic and digital processing systems means can offer great potential for rapid data acquisition and automatic analysis in engineering measurement and testing with high sensitivity. With the help of a computer and the appropriate software the plotting of the whole surface of a progressive addition lens will be easier and quicker. Also quicker will be the point measurement of the PAL's

In addition, the magnification of the fringe patterns have to change continuously in order to make the fringes visible. For less than 3 diopters measurements someone can keep the same magnification between 25 to 40x, because the difference between the fringes of the fringe pattern is easily distinguish. If someone wants to measure lenses of high power he must adjust the magnification respectively. Another disadvantage of the method is that the sign of the lenses + or - is not possible to get, only assumed.

The future instrument for the measurement of progressive addition lenses must be designed and engineered having in mind to make it the easiest-to-use lensmeter in the industry. It should be so easy to use, even by an inexperienced operator, after only a few minutes of training, so that accurate measurements can be obtained with the push of a button. Lens readings should be achieved in seconds. The prescription must be displayed and saved on the computer screen so it would be easy to read.

When compared with manual lensmeters, the instrument must perform measurements many times faster, so it can boost productivity. Unlike a manual instrument, operators should not need to focus and adjust the lens. It should be designed to remove the subjective nature of manual lensmeter readings, reducing operator error and allowing for objective measurements every time. Also, with the right modification the instrument could measure the oblique astigmatism that is seen by the user (wearer), which depends upon the position of the pupil compared with the position of the progressive lens.

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Appendix I.

Patent review

The first attempt for the production of multifocal lenses was registered to *Aves (1907)*. According to Aves the effect of progression of power was a result of the combination of the front and back surface, where the front surface was a convex cylindrical surface while the back was a conic one. Figure AI.1. is a reproduction from *Bennett (1970)* showing such a lens. As can be seen, the front and back are placed with their axis at 45° and 135° respectively. This produces an increase from top to bottom of the lens with a power variation from +6,00 to +9,00 D. Another drawback that this lens had was that the incorporation of cylindrical prescription was impossible.

Poullain and *Cornet (1916)(1920)* were the first to produce a multifocal lens where the power progression was made into a single surface. Such a lens had a principal section on one of its faces (front) with radii of variable increasing curvature. This was combined with a surface (back) of constant radii of curvature, providing the correction, spherical or cylindrical, for distance vision.

According to *Bennett (1970)* this principle section was an umbilical one. As *Sullivan & Fowler (1988)* mentioned an umbilical line is a locus of points where the curvature is the same in all directions. The curvatures of uniform progression employed for the principal section in such a lens may be, either spirals (Archimedean, logarithmic, multiple centre, circular evolving spirals), arcs of ellipse, parabola, hyperbola curves of the second degree or of higher degrees, algebraic or transcendent, symmetric or no symmetric curves. Figure AI.2. Illustrates the spiral of the variable radii of curvature and a cross section of such a lens.

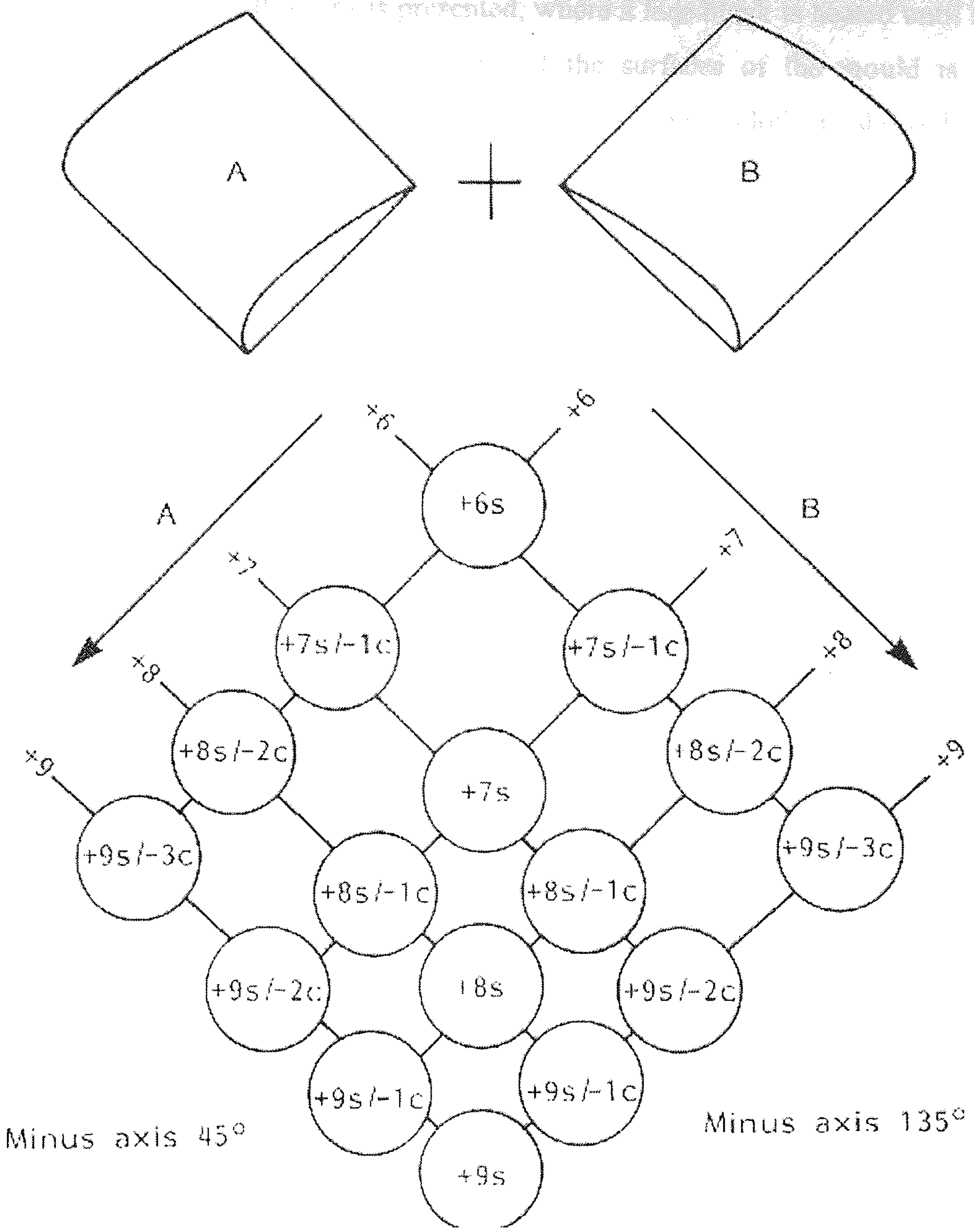


Figure AI.1. *Diagram, showing the power and astigmatism distribution over the lens surface, according to Aves design. (Reproduced from Sullivan & Fowler (1988)).*

Glancy (1923) describes a lens where the distance vision section is spherical while the intermediate section, are produced by the rotation of a circle around an axis Z. This circle has continuous radius change. Figure AI.3.b is the mathematical diagram of such a lens. The equation describing this surface is the following:

$$x^2 + y^2 + z^2 = (Ry - Rt)^2 + Rt^2 + 2Rt(Ry - Rt)\cos\omega$$

Also the manufacturing of this lens is presented, where a lens blank is heated until is softened and then pressed in a mould. One of the surfaces of the mould is a multifocal one. Then the lens blank is polished with a metal cloth as showed in Figure AI.3.c without losing its multifocal properties. According to Glancy, such a multifocal lens should be free from surface astigmatism at all points.

In, 1941, *Beach (1941)* had a different approach. His invention was to provide a multifocal spectacles lens, which resembles a blended bifocal. The multifocal surface is a surface of concentric revolution. This means that the progressive power section is composed of annular rings of different curvature and narrow width. Figure AI.4. shows front and sectional views of Beach's lens. As can be seen from the drawings this lens has a homocentric change of the radius of curvature for the intermediate and near section.

Another approach on progressive addition lenses was patented in 1949 by *Birchall (1949)*. The invention related to lenses having gradually changing focal power for use with spectacles, field and opera glasses, telescopes and other optical instruments.

According to the invention the lens has a gradual varying focal power characterised in that one of its surfaces is formed with a progressively changing curvature of "in-volute" form along the medial plane of the lens and in planes parallel thereto, so that in the case of a convex surface the curvature gradually increases from the top to the bottom of the lens, while for a concave surface the curvature gradually decreases from the top to the bottom of the lens. An "involute" form corresponds to a curve generated by a locus of points with variable power in a straight line.

According to the diagram of Figure AI.5, the dotted lines b and d are lines of intersection formed by planes perpendicular to the plane of the lens and parallel to the medial plane and these lines b and d are of involute form having an increasing curvature from the top to the bottom of the lens so that the lens has different focal powers at different points on any of these various lines b and d.

Aston University

Illustration removed for copyright restrictions

Figure AI.2. *Illustration of a spiral with radii of curvature varying in a continuous manner. Such a spiral incorporated on the front surface of the lens while the back surface has a constant radius of curvature, gives a multifocal of this type (According to Poullain & Cornet, 1916)*

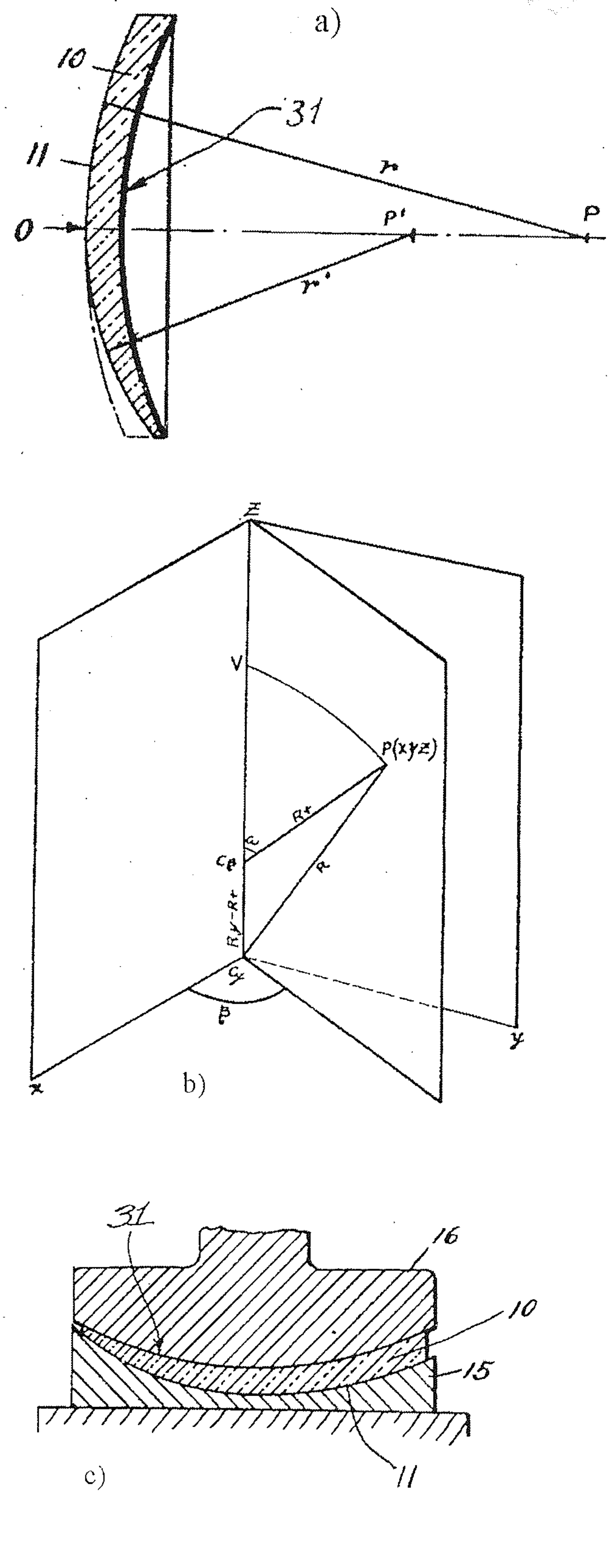


Figure AI.3. *Glancy's ophthalmic lens and the method of grinding it. a) Is a cross-section view of the lens. b) Is the mathematical diagram of the multifocal surface, while c) shows the mould 10, for the multifocal surface. (After Glancy, 1923)*

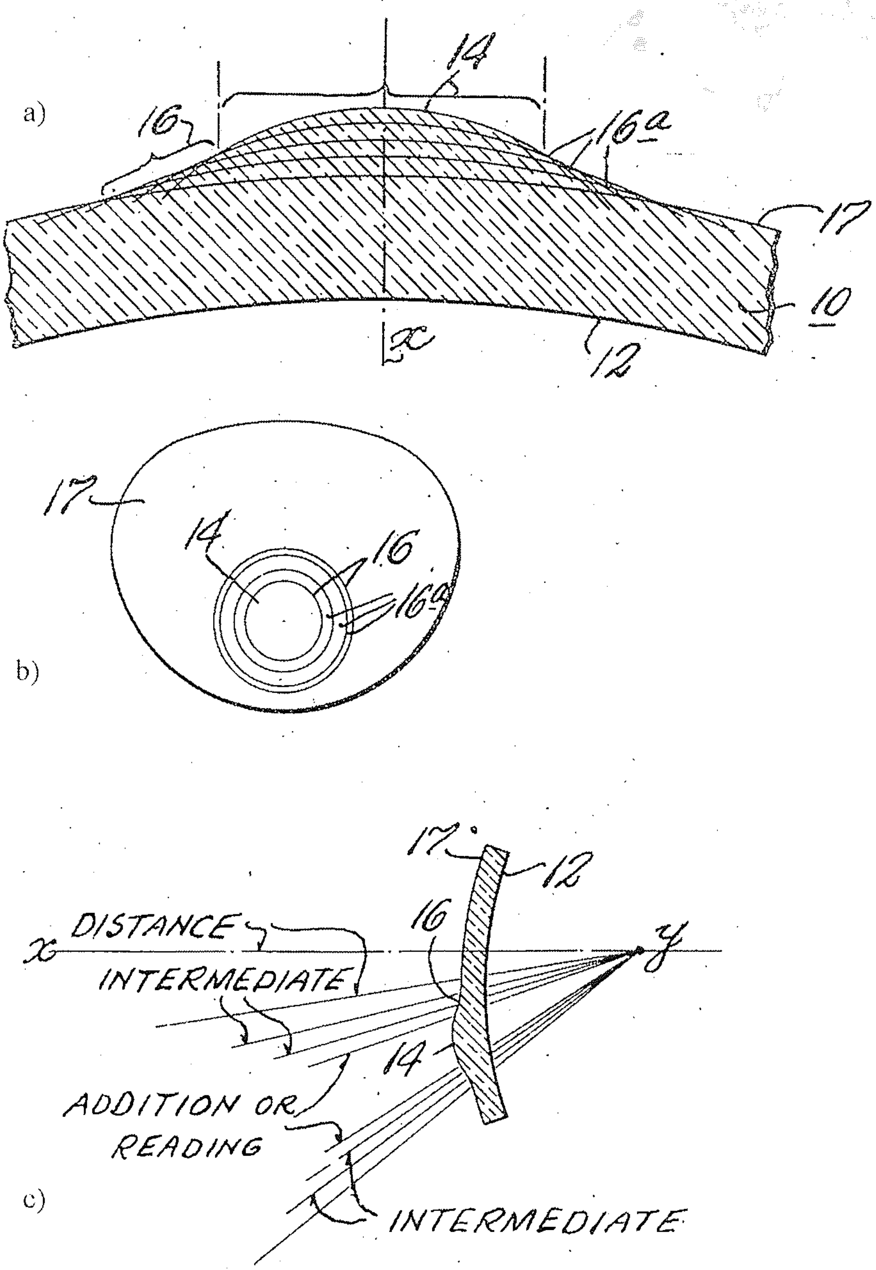


Figure AI.4. *The multifocal lens, according to the. Beach approach. a) Cross-section of the central portion of the lens. b) Face view of the lens c) Cross- section showing the areas of vision of this multifocal lens. (After Beach, 1941)*

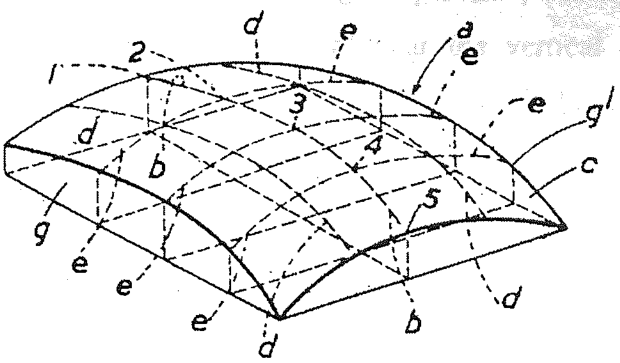


Figure AI.5. *Diagram of H. J. Birchall's lens. b and d are the planes having variable focal power for a plano-convex lens. (After Birchall, 1949)*

Spiegel (1947) proposed a method of producing an optical glass substantially where the refractive index varied continuously through at least a part of the lens. He used a mixed molten batch, containing ingredients of different refractive indices and densities. This batch contained different oxides of which one consists of a substantial quantity of cadmium oxide. The batch contained approximately 13.5%o of boron oxide, 15%o of silicon oxide, 17%o of lanthanum oxide, 34.8%o of barium oxide, 13.3%o of cadmium oxide, 4%o with oxides such as boron, silicon, lanthanum, barium and cadmium and a minor quantity of each of the oxides of beryllium and zirconium.

The batch was maintained at approximately 1300° C. for one hour and then gradually the temperature was reduced to 1090° C. in approximately forty minutes. Then the temperature was reduced while the batch was still in a quiescent state to approximately 600° C. and maintaining it at this temperature for approximately two hours, and finally gradually reducing the temperature of the batch to normal. This whole procedure passing from one temperature condition to the other and the use of the above mentioned oxides are responsible for the index variation.

The ophthalmic lens constituting *Kanolt's (1959)* invention had a multifocal surface on the back surface of the lens, while the other surface could be spherical, cylindrical or toroidal incorporating the prescription. The shape of the multifocal surface had a reference vertical plane, which was a tangent to the lens centre. The contour lines of such surface were in the upper portion concave downward near the vertical axis of the lens and convex downward near the marginal portions, while those in the lower portion of the lens were convex downward near the vertical axis and concave downward near the marginal portions. The lens had a dioptric power, which increased gradually and continuously from the top to the bottom of the lens and had no visible line of demarcation along the vertical axis of the lens between the portions of different dioptric power.

As Kanolt mentioned, it is almost impossible to produce progressive lenses without having an amount of astigmatism in some parts of the lens.

In one of his embodiments the amount of astigmatism must not exceed 3/8 of a dioptre in the central part of the lens and not more than 5/8 of a dioptre at the margin. The designs (four) of lens surface that were described by Kanolt are for a lens diameter of 40 millimetres, for a given addition of two dioptres and a material with a refractive index of 1.5. Considering a lens shown in Fig. AI.5, the lens surface is divided into two areas designated as areas A and B. The equation of the surface in area B is:

$$z = 0_4 145y^3 + 0_4 4975x^2y - 0_5 156x^3y + 0_8 405y^5 - 0_7 23625x^2y^3$$

And that of the surface of area A is:

$$z = 0_4 145y^3 + 0_4 4975x^2y + 0_5 156x^3y + 0_8 405y^5 - 0_7 23625x^2y^3$$

Where the subscripts in the equations indicate the number of zeros that follow to the right of the decimal point. The dividing line between the two areas is the line x = 0. All four designs present skew symmetry relatively to the horizontal axis of the lens having zero dioptric power on, with negative power above and positive below. With such designs Kanolt moves unwanted astigmatism to other areas than the one illustrated in Figure AI.6.

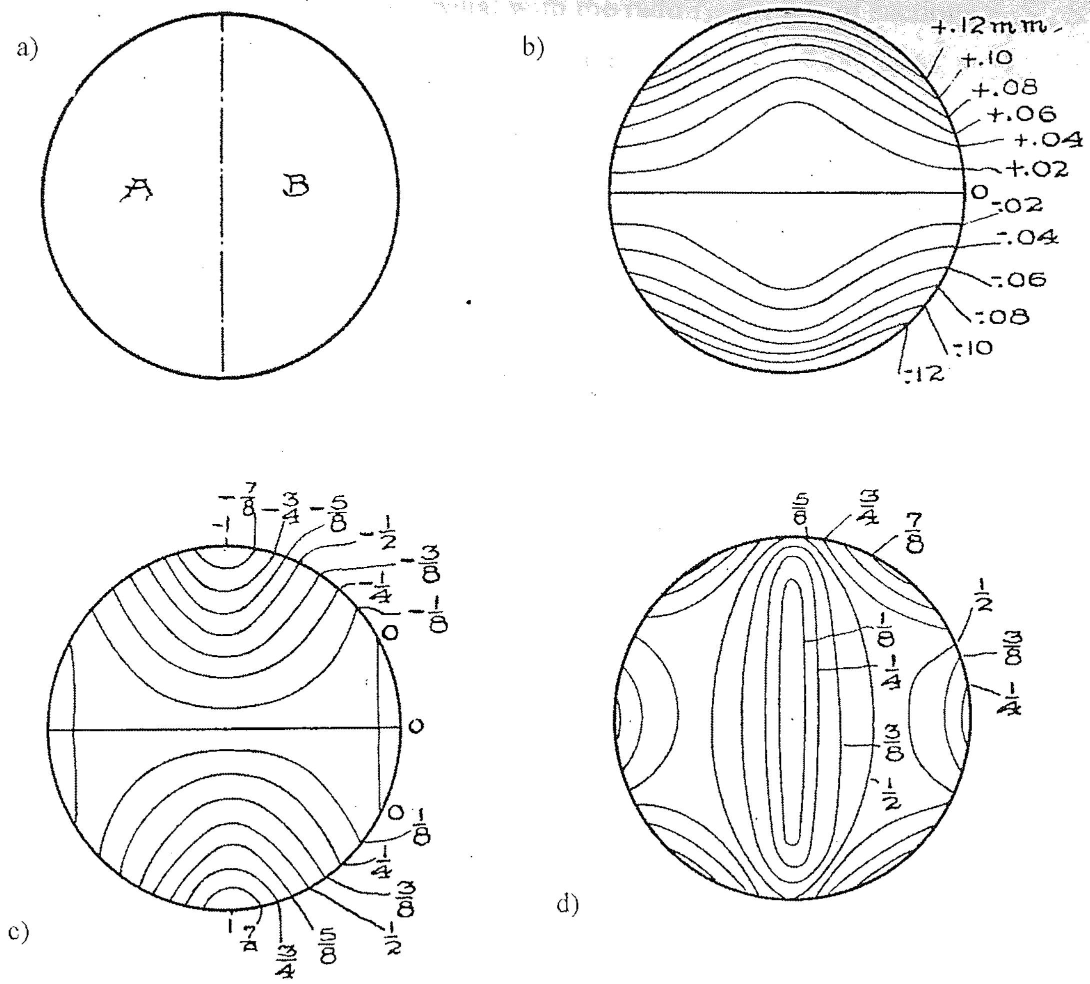


Figure AI.6. *Lens according to Kanolt. a) Is a design of the lens surface, which is divided into two areas. b) Shows the contour lines of the surface of the lens with preference to a plane tangent to the lens surface at its centre point and with the contour lines being placed at 0.02 mm. intervals. c) Shows the distribution of mean dioptric power at 1/8-dioptre steps. d) Shows the distribution of the astigmatism with lines at 1/8 dioptre steps. (After Kanolt, 1959).*

The first time that multifocal surfaces were named "progressive surfaces" was in the patent of *Maitenanz (1959)*. Also he was the one who first designed a commercially available progressive addition lens. He was the one who explained the nature of a progressive surface for ophthalmic use. Figures AI.7.a, b show the progressive lens and surface. The main radius of curvature is variable according to a law, where r = f (α), α being the angle showed in Figure AI.7.a. Explaining the progressive surface, it must be understood that the principle radii r, r', r'' in the medial plane A, B, C at sections S, S', S'' of the lens are equal with the radii r_1, r_1', r_1'' of sections S, S', S'' which are orthogonal to the medial plane A, B, C.

Also the following relation exist

$$r > r' > r''$$

In any other plane such as A', B', C' this equality does not exist and that is why astigmatism results in such areas, as showed in Figure AI.7.b. Figure AI.7.c is a progressive form surface for ophthalmic use, where the upper section of the lens surface is a conventional constant power surface while the lower section has a progressive type.

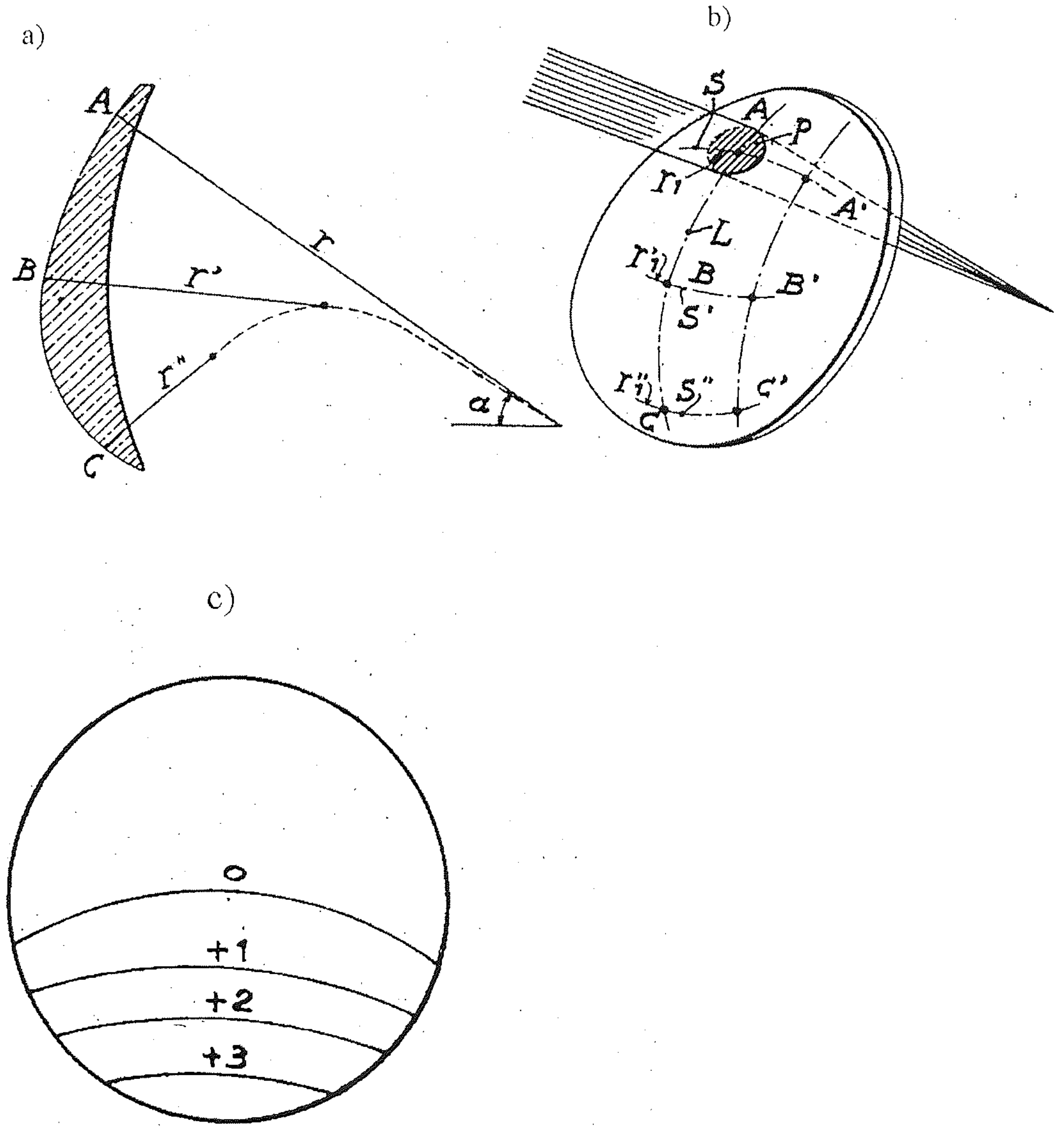


Figure AI.7. *a) Is a cross-section view of the lens, b) is a description of the front progressive surface, c) shows the distribution of the power profile in the front surface of the lens. (After, Maitenanz 1959).*

Also in 1959 *Maitenaz (1959)*, for the Societe Industrielle et Commerciale des Ouvriers Lunetuiers, produced a machine for grinding such progressive lenses. The progressive lens produced takes into consideration binocular vision. Instead of having the plane of symmetry of the two lenses inclined nasally 8 to 10° related to the vertical axis of the lens in order to follow the pupillary convergence from far to near according to the function of the law of convergence –accommodation, the lenses have a curved line AB with a locus of points having their main radii of curvature equal to each other. Such a law takes into consideration the vertical and horizontal prismatic effects as showed in figures AI.8.d and e.

Naujokas (1969) on behalf of Bausch & Lomb Incorporated introduced a synthetic plastic ophthalmic multifocal lens, where the main lens had a uniform refractive index while a section of the lens had a uniform index gradient. This invention uses methods for polymerising organic resins by diffusion of monomers across a liquid interface with subsequent polymerisation, where the resulting optical elements have variable refractive index.

These optical plastic materials are produced in such a way that an interface is established between monomeric liquids. These liquids are put in a controlled path of diffusion and subsequently polymerised, producing a non-homogeneous optical solid material having an intermediate zone of refractive index gradient from a higher-index first polymer to a lower-index second polymer through a co-polymeric portion having variable composition.

Such a multifocal lens can be produced by layering of diallyl phthalate and allyl diethylene glycol-2-carbonate liquid monomers in a lens mold, diffusing the monomers across the liquid interface to establish a composition gradient, and polymerising the allyl monomers in situ to create a variable-composition copolymer zone having a corresponding index change. Suitable resins for use in this invention include the acrylic polymers and copolymers. Methyl methacrylate (n=1.48-1.50 for the solid resin) may be paired with styrene (n=1.59-1.60 for polystyrene), or a mixed monomer of methyl methacrylate and styrene (n=1.53-1.56 for copolymer) may be paired with either or both. Another compatible acrylic monomer is alpha-methyl=styrene and methyl methacrylate co-monomer (*n=1.52* for copolymer). The pure monomers and mixed monomers may be cured after diffusion by catalysts and/or thermal reaction. In order for diffusion step to be controlled, isothermal conditions and a predetermined diffusion rate are needed.

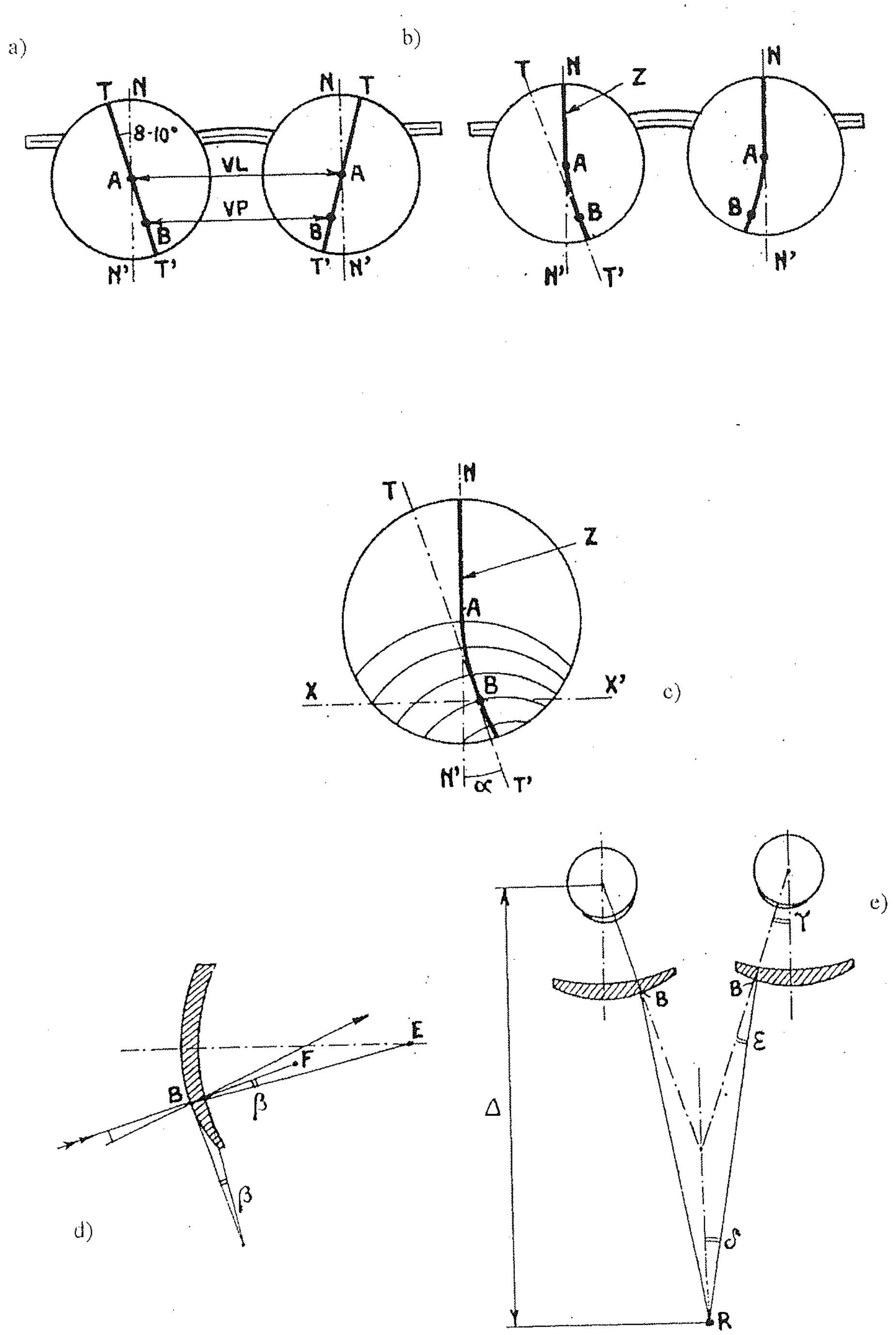


Figure AI.7. *The progressive lenses according to. Maitenaz. a) is a front view showing a pair of progressive lenses of previous design, b) is a front view showing a pair of progressive lenses according to Maitenaz. c) Illustrate a front view, of the lens progressive surface d) the vertical prismatic effect, e) the horizontal prismatic effect when the eyes accommodate. (After Maitenaz, 1959)*

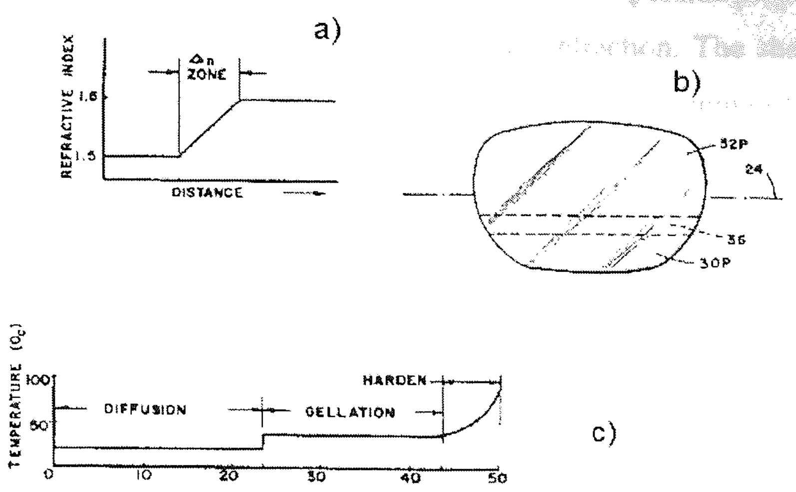


Figure AI.8. *The lens and the diffusion plots of A. A. Naujokas' lens. a) Is a plot showing changes in refractive index of a solid resin. d) Is a cross-section of a lens mold for casting such lenses. e) Is a front view of a plastic lens having multifocal portions and a continuously variable refractive index portion intermediate. f) Is a time and temperature diaphragm of a typical process cycle for diffusing allyl monomers and thermosetting the diffused material according to a predetermined program. (After Naujokas, 1969)*

Hamblen (1969) for Bausch & Lomb Incorporated, like Spiegel and Naujokas, patented a lens with gradient index of refraction. It was a single lens of uniform refractive index, where metal ions had been diffused to produce a change in the index of refraction. This change of refractive index took place at a depth at the outer areas of one of the faces of the lens and then portions of the diffused surface were removed to produce a lens presenting different refractive index from the top to the bottom of the lens. Figure AI.9. Shows how such a lens after the diffusion can produce a variable refractive index in one of its faces.

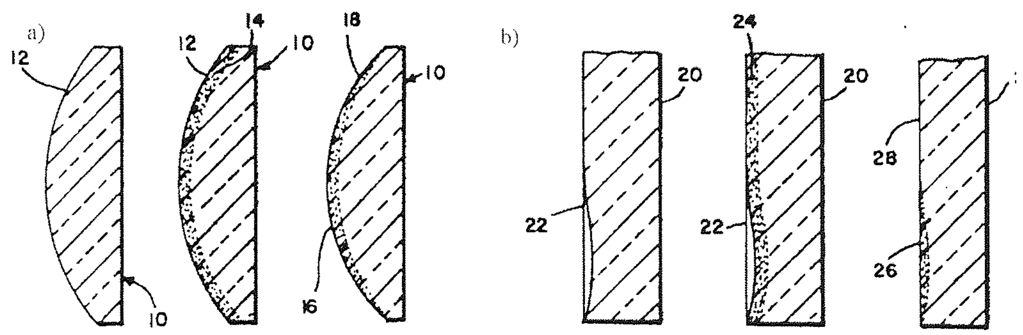


Figure AI.9 *a) are cross-sections of a lens where diffusion took place, while b) are cross-sections of an aspheric perform treated with an index-changing material and ground to a flat surface to produce an optical element having aspheric characteristics. (After Hamblen, 1969).*

Hensler, et al (1970) again for Bausch & Lomb Incorporated proposed a fused multi-focal, with a gradual change in the index of refraction. The shape of the diffused zone was a straight line. The refractive index at the beginning of the diffusion zone was identical to the refractive index of the section of the lens for distant vision while at the end of the zone the refractive index was identical to the section for near. The method for changing the refractive index was obtained by migration of metal ions (preferably AgCl as diffusant) into the surface of the glass.

A similar lens was proposed by *Rosenbauer (1971)* also for Bausch & Lomb Incorporated. In this patent, selected metal salts (silver chloride) are diffused into a glass blank The penetration of the diffusant across the surface is about 2 mm. Then a segment of higher refractive index is fused into the treated glass blank shaping the second lens portion. The difference (Δn) in the refractive index produced is about 0,025 up to 0,07 if the diffusant is thallium chloride.

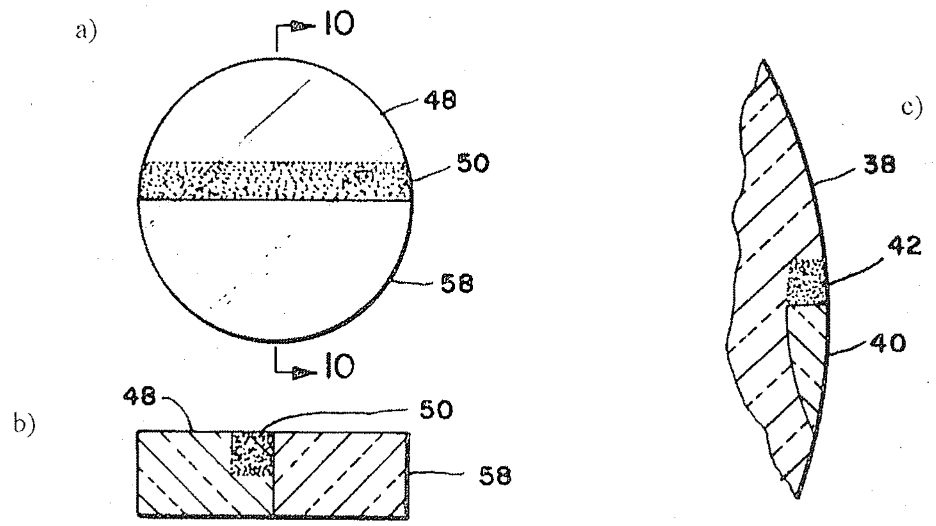


Figure AI.10. *Drawings of the lens according to J. R. Hensler, et al. a) is a front view of a blank illustrating the far intermediate and near section of the lens. b) Is a cross-section along lines 10-10 of Fig. a) showing the depth of the diffusant added. c) Is a cross-section of a finished lens. (After Hensler, 1970)*

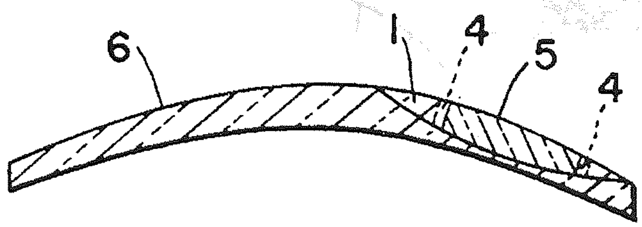


Figure AI.11. *The lens proposed by C. Rosenbauer. Sections 4 are transition zones around the near segment 5. (After Rosenbauer, 1971)*

A multifocal lens was provided by *Volk (1971),* having a convex aspheric front surface, and a back toric surface. The progression of power increased from the top to the bottom of the lens. This front surface was a nonaxial portion of a surface of revolution, where in all meridian sections this progressive surface consisted of identical elliptical arcs. The back toric surface was selected in a manner to neutralize the resulting astigmatism from the front surface along the principal meridians of the lens. This progressive surface had astigmatism constant at all its points. The total astigmatism presented outside the vertical principal meridian was at directions 45° and 135° sideways of the vertical principal meridian and increased in lateral distance from the principal meridian. The equation giving the amount of astigmatism at any point on such lens is

$$V = \frac{6(n-1)(A^2-B^2)(AB)^6hab}{(A^4b^2+B^4a^2)^3}$$

Where, n is the refractive index, A and B are the semi major and semi minor axis of the ellipse arc in the principal meridian, a and b are the coordinates at the given point measured and h is the distance from the principal meridian. In order to produce the front progressive surface four elements are important: a) the radius of the cam circle b) the inclination of the cam circle c) the azimuth of the cam axis d) the skewness of the cam centre used to produce such a surface.

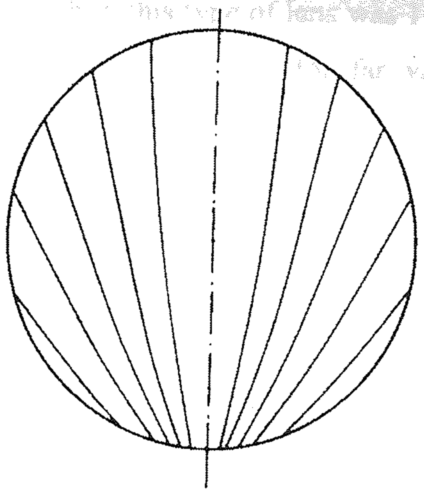


Figure AI.12. *Front view of Volk's lens showing the distribution of astigmatism exhibiting by the lens (After Volk, 1971).*

Maitenaz (1972) on behalf of Societe Des Lunetiers, Paris, France, proposed an improved type of progressive lens. It was an ophthalmic lens with a front surface having an umbilical curve, which is the progression umbilical curve, along which the radius of curvature evolved so as to provide the desired progressive variation of the focal power of the lens. An umbilic curve is a curve where at all of its points the two main radii of curvature are equal.

The main characteristic of the progressive surface is the umbilical line MM' (Fig.AI.13.a) along which the radius of curvature of the surface evolves according to a law of continuous variation of the focal power of the lens. The curve R illustrates the evolution of the osculating radius, showing the conic sections, respectively on each section of the lens surface. (Fig. AI13.c)

A_0 A_2 : section of flattened ellipse.

A_2 : circular section.

A_2 A_5 : section of elongated ellipses.

A_5 : parabolic section.

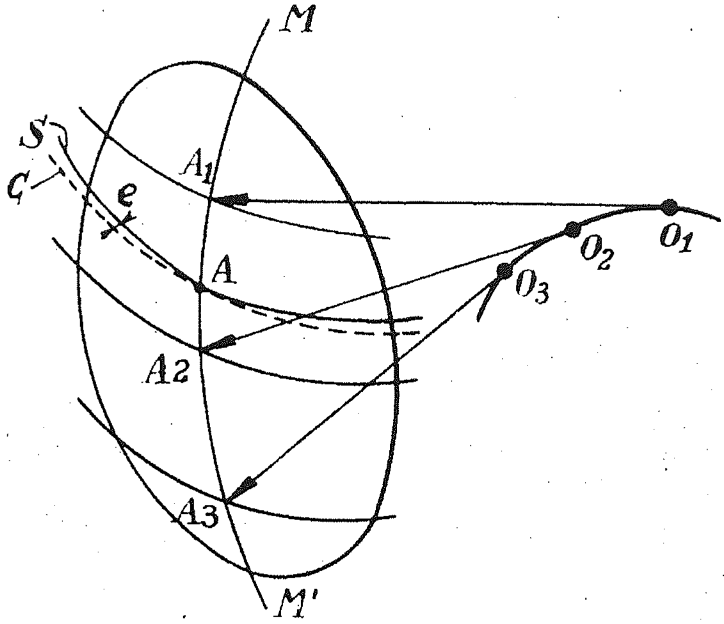
A_5 A_7 : section of acute hyperbolas

A_7 : equilateral hyperbola

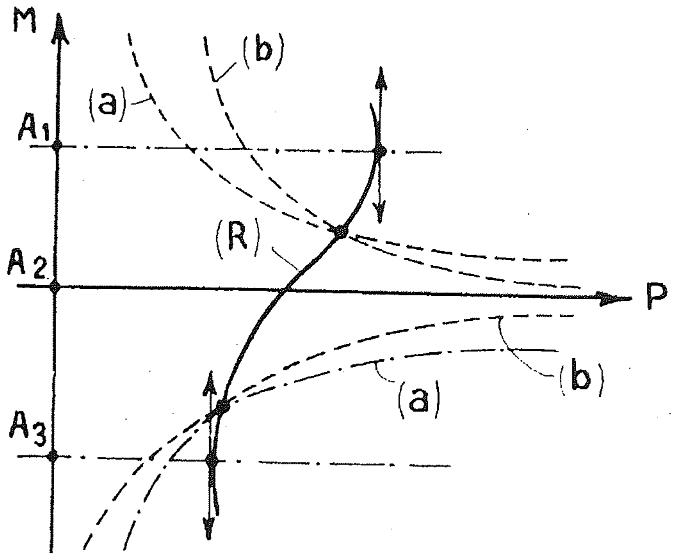
A_7 A_8 : section of obtuse hyperbolas.

The progressive corridor length in this type of lens was 14 mm. With such a lens the improvement related to aberrations is great for far vision but is much less in intermediate and near vision.

a)



b)



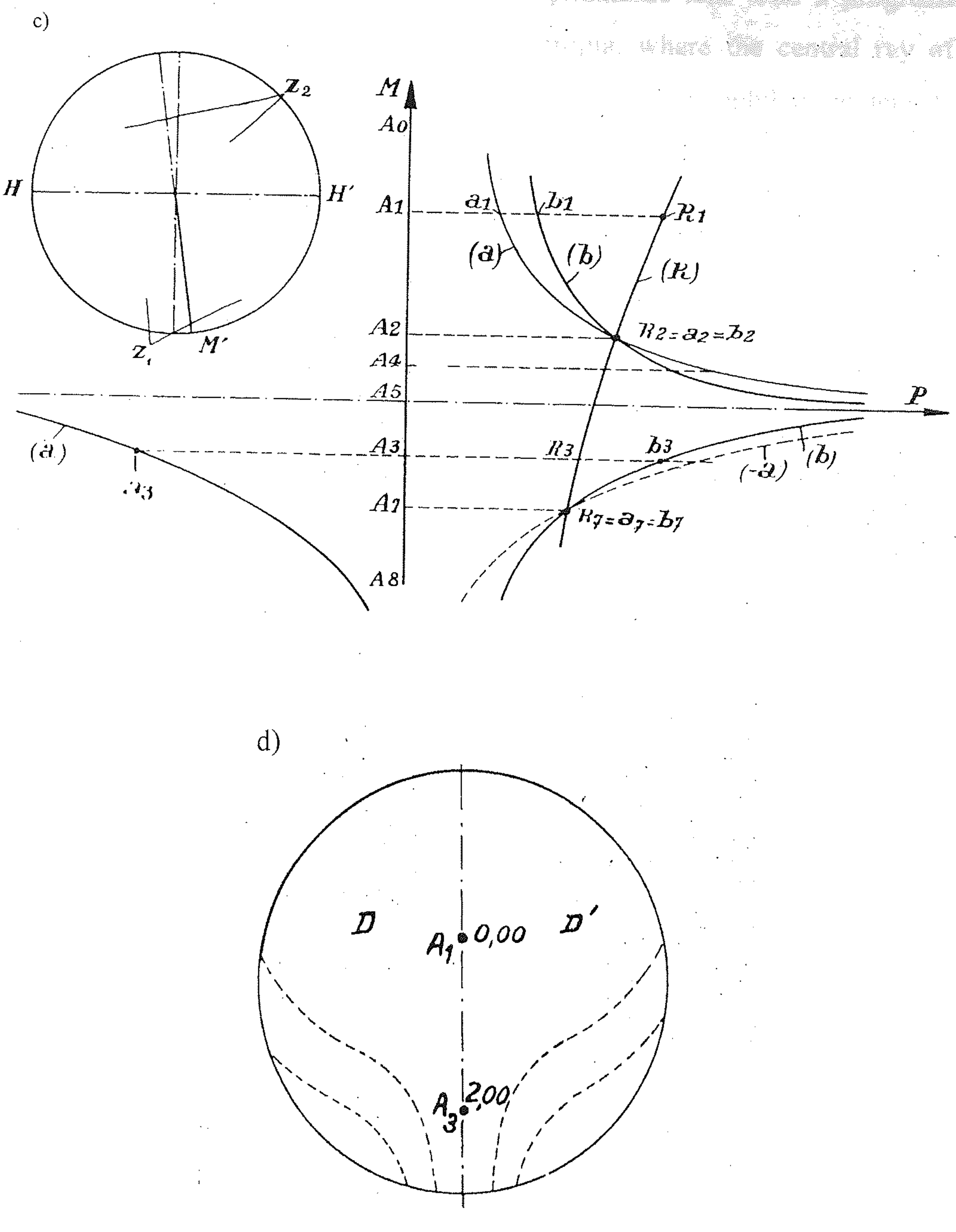


Figure AI.13. *The progressive lens according to Maitenaz. a) Shows diagrammatically the surface of progression produced by evolutive conic sections and the umbilical meridional curve. b) is a diagram of the power variation along the umbilical meridian c) is a diagram showing the conic sections consisting the progressive surface of the lens. d illustrates the iso-astigmatism curves of such a lens. (After Maitenaz, 1972)*

Tagnon (1973) proposed a concavo-convex ophthalmic lens with a progressively varying focal power for correcting high ametropia, where the central ray of the direction of far vision gaze was 27 to 28 mm. Such an ophthalmic lens had a spherical surface of + 12.00 dioptres spherical lens where for an angle of gaze of 30° was in fact a toric lens having a spherical power of + 11.50 dioptres and a cylindrical power of + 4.50 dioptres due to the aberrations. For correcting such a progressive addition lens the aspheric profile of the correction surface used, in the upper part of the lens corresponding to the far vision, these aspheric curves are circular which clearly points out the fact that this far vision portion is a portion of an aspheric surface of revolution. In the lower section of the lens, these curves are perpendicular to the vertical axis, which is a result of the choice of a surface, which is symmetrical with respect to the vertical meridian of progression. These curves get closer to one another concentrating in a small area of the lens. This results that the useful portion of the progressive surface has been as much as possible widened at the expense of the smoothness of small lateral zones, which give large deformations or aberrations making them unusable. (Fig. AI.14a)

The tangential radius and the sagittal radius at the optical centre were made identical, (Fig. AI.14b) and the meridian plane of progression, which was the plane of symmetry for the whole progressive surface, constituted a plane of oblique symmetry in the horizontal direction for at least the intermediate surface portion of the progressive surface of the lens (Fig.AI.14c). In such a lens aberrations are corrected for far vision and for near (0.33 m) where there is no astigmatism or field curvature. The corridor length of the progression was 14 mm.

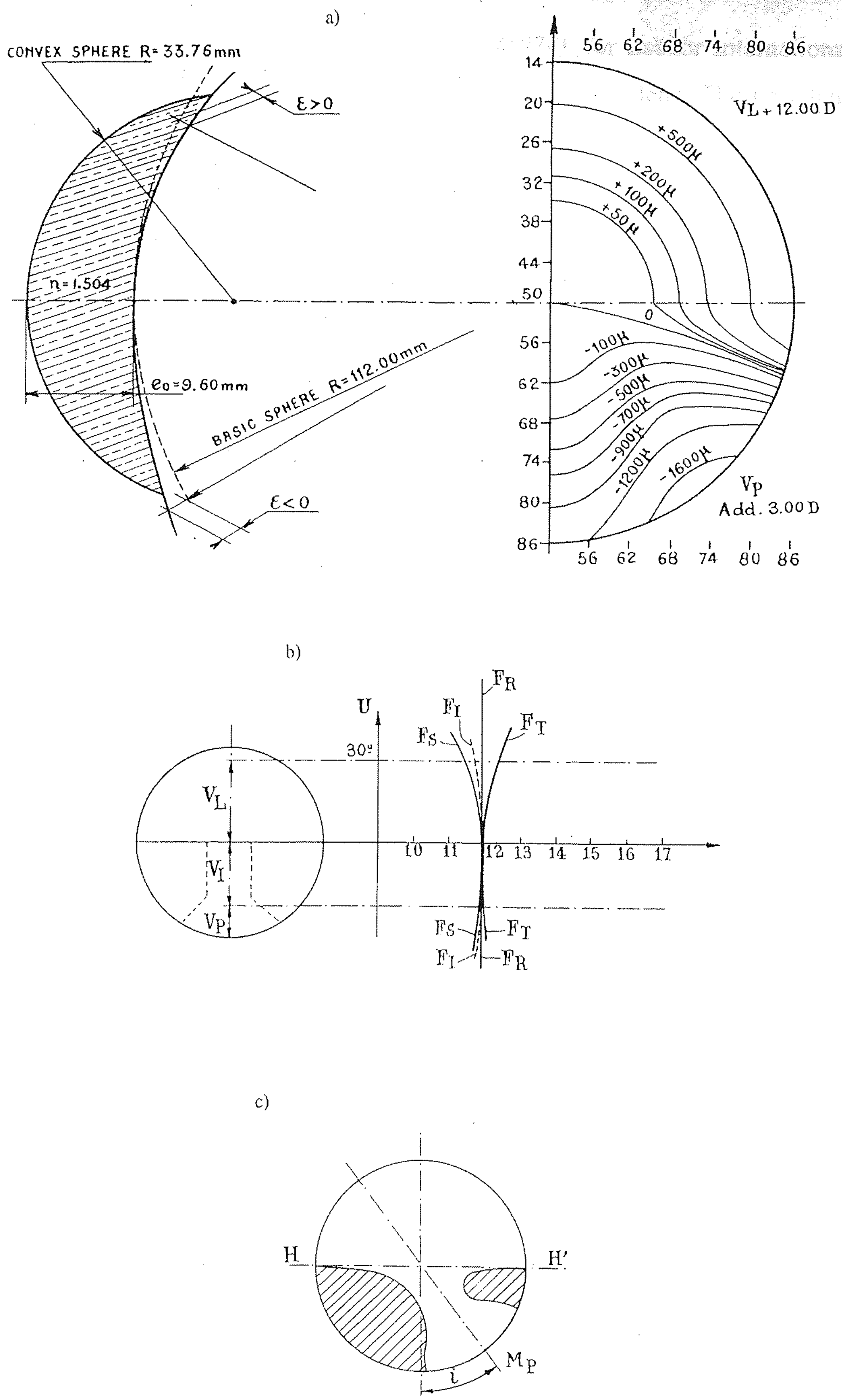


Figure AI.14. *Tagnon's progressive lens for high ametropia. a) Shows the iso-discrepency curves of the aberration correcting progressive surface of the lens; b) is a diagram showing the corrected aberrations, according to F_T and F_S of the lens on the umbilical curve. c) Shows a modified form of the progressive lens of the invention, with an oblique symmetry. (After Tagnon, 1973)*

Continuing his work with varifocals *Maitenaz (1974),* for Essilor International this time, made some improvements to his previously patented lens. The new lens had three zones respectively for distant vision, intermediate distance vision and near vision, where an oblique meridian passes through the optical centre of the lens and traverses said zones. This main meridian was inclined nasally downwards along an angled path according to the wearer's convergence. The zone for intermediate vision had, at each point, a minimum curvature (*Cmin.*), and a maximum curvature (*Cmax.*) along this main meridian. These two curvatures at each point along this meridian are equal. On either side of the main meridian iso-astigmatic curves exist (areas of equal value of astigmatism). The equation related to *Cmin.* and *Cmax.* Is the following relation:

[Cmax. -Cmin.]=N,

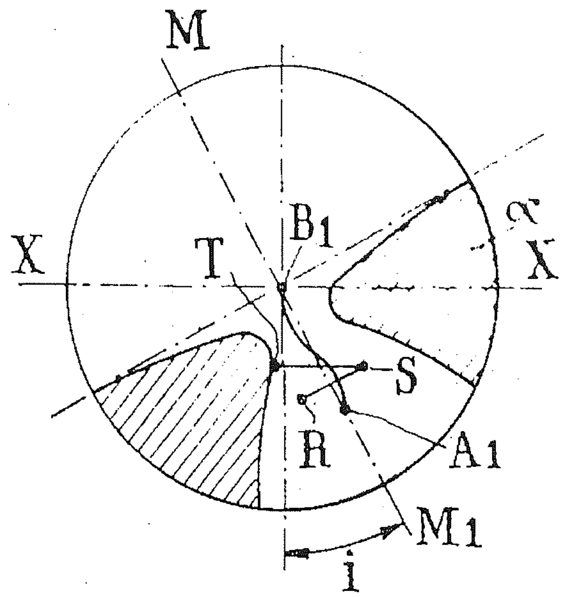
Where N has a given value, which satisfies the relation:

N<=1/(n-1),

n being the refractive index of the refractive material.

The previous progressive lens when mounted on a frame had its main meridian inclined for about 15° from the vertical plane clockwise or anti-clockwise for the right and left eye respectively (Fig.AI.15a). However this caused an astigmatism aberration zone of different values, thereby resulting in an uncomfortable vision. With the new design the lateral field of vision is preserved free of astigmatism (less than 0,3 D, which according to Maitenaz is the acceptable limit of astigmatism tolerated) both in the distant vision area and in near. In the intermediate zone of vision, the field is limited by iso-astigmatism curves, which are in an oblique symmetry relationship with respect to meridian MM_1, thereby preserving comfort of vision. In binocular lateral vision the wearer observes astigmatism, which is equal for both eyes (Fig.AI.15b).

a)



b)

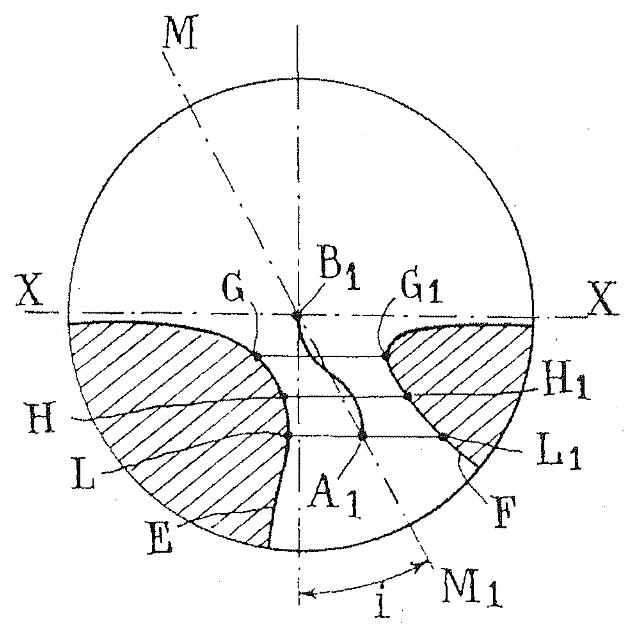


Figure AI.15. *Maitenaz's progressive addition lens. a)Shows diagrammatically the distribution of the astigmatism aberrations in a lens according to previous design. b) Shows diagrammatically the distribution of the astigmatism aberrations in a lens according to the invention. The asymmetrical profile of the surface related to the meridional axis MM_1 is proposed in order to give the wearer better binocular vision. (After Maitenaz, 1974).*

In *US Patent 3,910,691 (1975)* Maitenaz for Essilor for the first time used the terms "static vision", and "dynamic vision". Static refers to when the wearer's eye looks at an object through the lens, the light beam forming the image of the object constantly passes through the same portion of the lens surface. On the other hand, the term dynamic refers to the opposite of static. It has to do with the relative movement between a) the eye and the lens, when the eye rotates about its centre of rotation, with the wearer's head remaining stationary, b) the eye and the object, when the observed object stays stationary but the spectacle wearer rotates his head, while the eye remains fixed on the object.

The lens was characterized by a considerably improved comfort in case of dynamic vision. Such a lens, is characterized essentially in that, at each point B_{ij} of the aspheric surface, the cross-section of this aspheric surface taken along a substantially vertical plane parallel to the plane of the umbilical curve is a curve of which the curvature C_{Bij} at this point B_{ij}, follows the relationship:

$$\left| C_{Bij} - C_{Ai} \right| \leq N$$

C_A is the curvature of the umbilical curve at point A_i of this curve which is located on a same horizontal section as said point B_{ij}, and N is a number having a predetermined value complying with the following relationship:

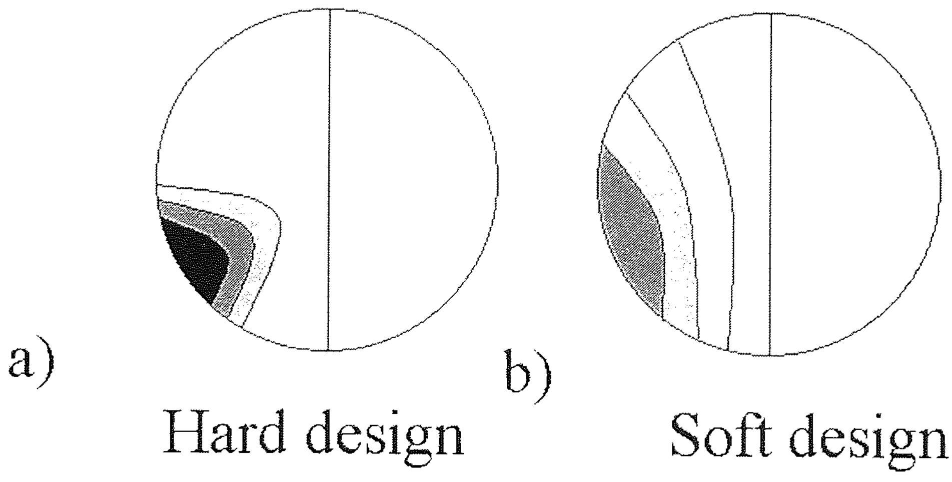
$$N \leq 3.5\ A$$

A is the power addition in dioptres, between the distant-vision centre and the close-vision centre.

The aspheric surface produced comprised of: a) the umbilical curve MM_1 with a desired law of progression b) two other umbilical curves passing through the distant-vision centre A_1 and through the close-vision centre A_3 respectively, perpendicular to the umbilical curve MM_1. At the two points, which lie respectively on the two other umbilical curves and which are equally spaced from the umbilical curve MM_1, the lateral magnifications have the same horizontal component. Also along the two other umbilical curves the vertical component of the prismatic effect be constant.

In the diagram of Fig. AI.16c, the curves 6, 7 and 8 illustrate the curvature variation of the umbilical curve MM_1, of the vertical section Σ_{10}, and of the vertical section Σ_{20}, respectively. These sections are spaced about 10 and 20 mm from the plane of the umbilical curve MM_1. By way of comparison, Fig. AI.16d show the curvature variation (curve 12) of a vertical section located at a distance of 20 mm from the umbilical curve MM_1 of the aspheric surface of a lens constructed according to *U.S. Pat. No.3.687.528*. This reduction of the vertical and horizontal distortion is very important, because, although under static vision condition the human brain will rapidly compensate the distortion, it operates very slowly under dynamic vision condition.

Sullivan and Fowler (1988) show diagrammatically the distribution of astigmatism according to the static and dynamic conditions. The static vision refers to ***hard design***, where the astigmatism spreads in a smaller area on the lens surface but is of higher value than that of ***soft design*** referring to dynamic vision. As it is seen in soft design the astigmatism spreads over a larger area on the lens surface. (Figs. AI.16a, b)



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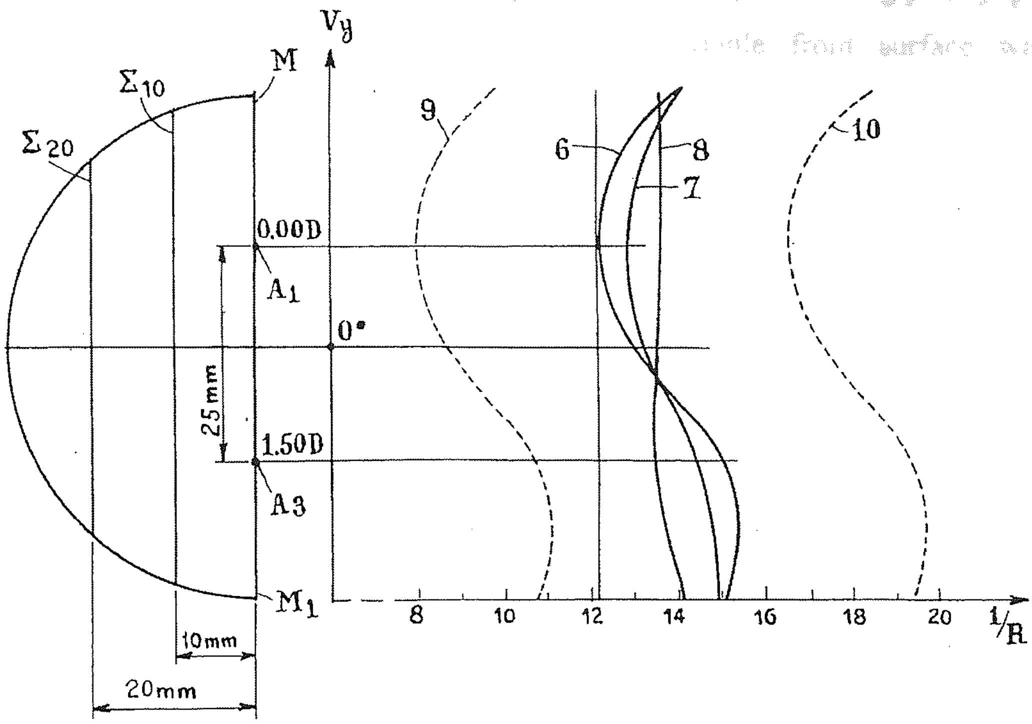


d)

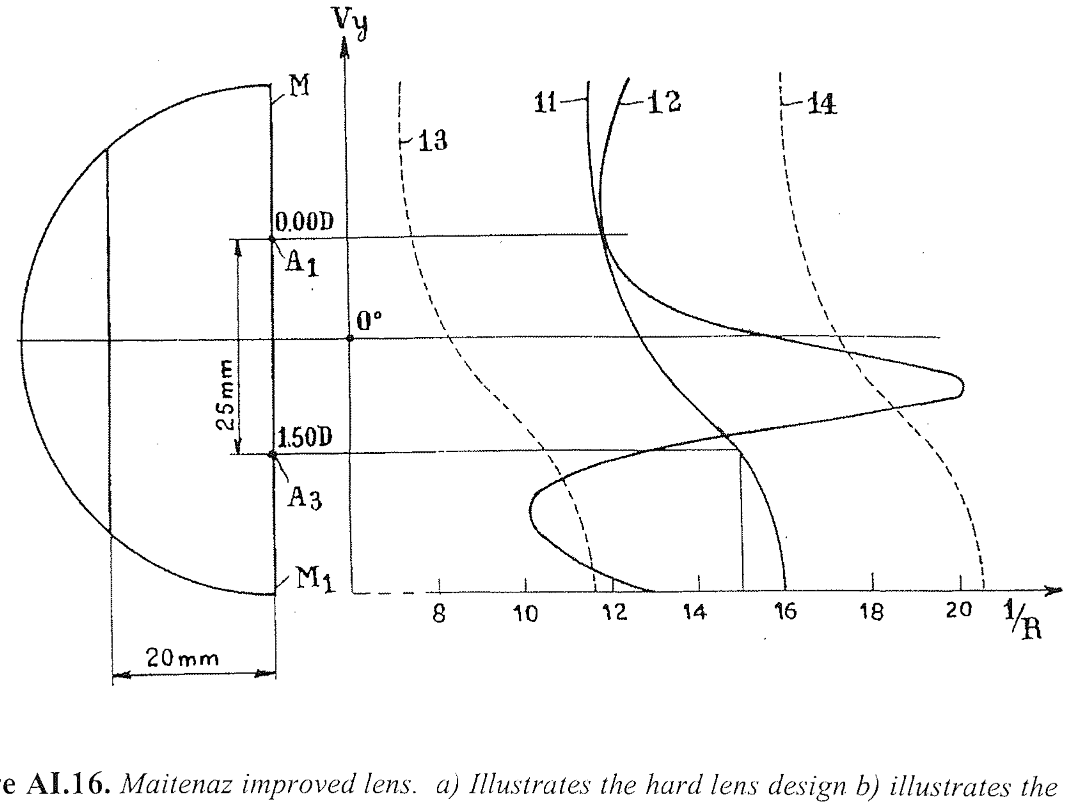


Figure AI.16. *Maitenaz improved lens. a) Illustrates the hard lens design b) illustrates the soft lens design c) Diagram showing the curvature variation of the two vertical sections parallel to the plane of the vertical umbilical curve and spaced from this plane by 10 and 20 mm, respectively. d) Shows by way of comparison the curvature variation of a vertical section spaced 20 mm from the umbilical curve of a previous progressive lens. (After Maitenaz, 1975)*

Volk (1976) in 1976 presented a multifocal ophthalmic lens for correcting presbyopia in physiological conditions and in aphakia. The variable front surface was geometrically and optically regular, continuous and umbilical and had a pair of intersecting orthogonal principal planes. The first plane, which was horizontal, intersected the variable surface normally at all points in a circular or elliptical arc, which is called a "great arc". This great arc, when elliptical, had its prolate point coincide with the axial point of the variable surface. The second plane was vertical, intersecting the variable surface normally at all points on the principal curve, about which there was symmetry. Above the great arc the surface was a surface of revolution and below the curvature increased progressively in conic sections. Both two planes were planes of symmetry. The back surface could be spherical of toric for correcting patient's astigmatism.

Figure AI.17a shows the front surface of Volk's lens and the two previously mentioned planes lying on the variable front surface. Figure AI.17b shows the variable front surface of the lens WQVP and how is constructed. Arc QBP is the principal curve, where B is the axial umbilical point. Both arcs BP and QB are elliptical, but when QB being prolate and BP being oblate, then the whole surface consists of conic sections having eccentricity $e > 0$ and great arc is also WBV elliptical. When QB is an oblate ellipse then the great arc WBV is circular, having no astigmatism along its points.

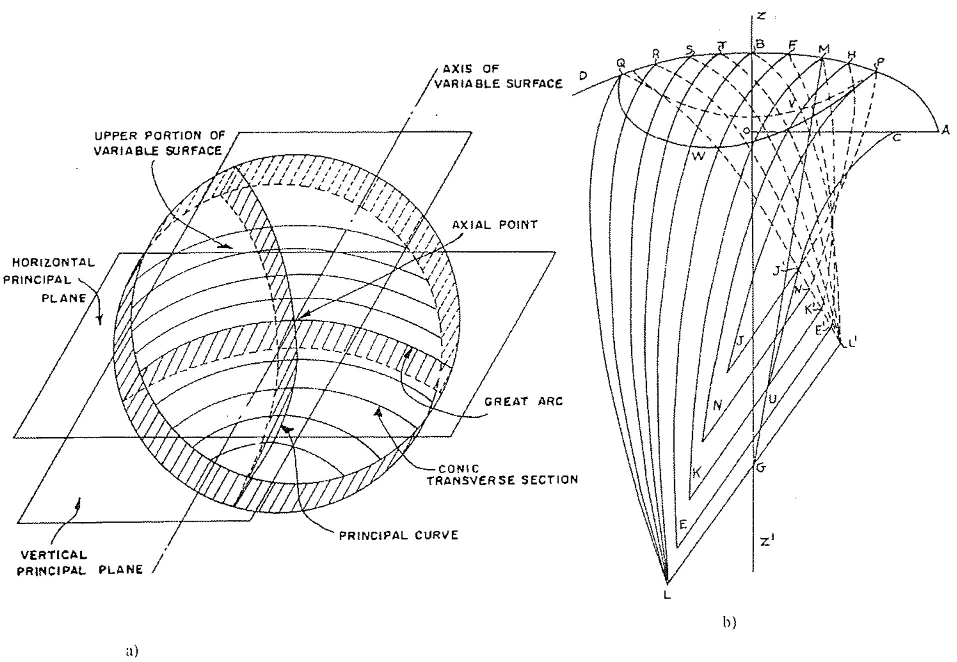


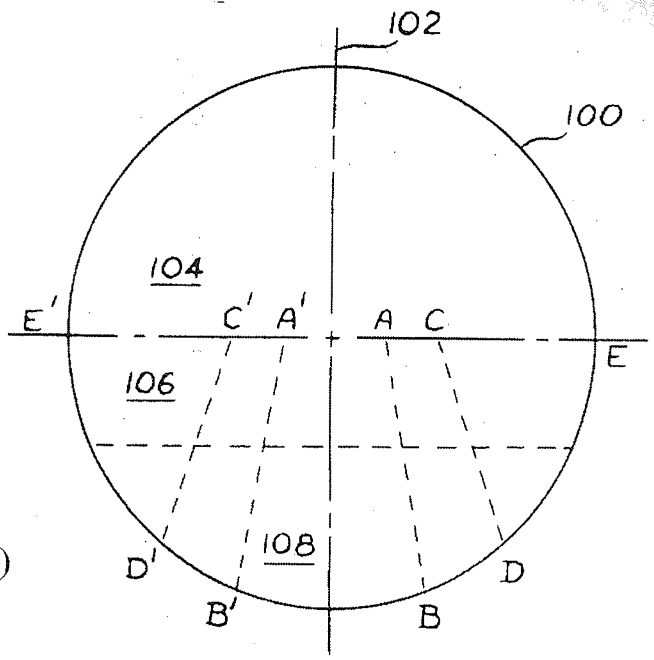
Figure AI.17. *Volk lens for aphakics. a) Diagrammatic view of the lens showing the horizontal and vertical principal planes, the variable surface of the lens, the great arc and the principal curve respectively. b) Diagrammatic view of the variable surface WQVP of the lens showing the principal curve QBP and transverse sections of the variable surface as circular arcs above the circular great arc WBV at R, S and T, and as conics at F, M and H below the great arc. After Volk, 1976)*

A multifocal ophthalmic lens was described by *Winthorp (1977),* on behalf of American Optical Corporation. The surface of the lens, which is progressive (front surface) as in all so far progressive lenses consist of three areas useful for the wearer a) distant-vision area with constant power b) near-vision area with also constant power c) intermediate-vision area with variable power.

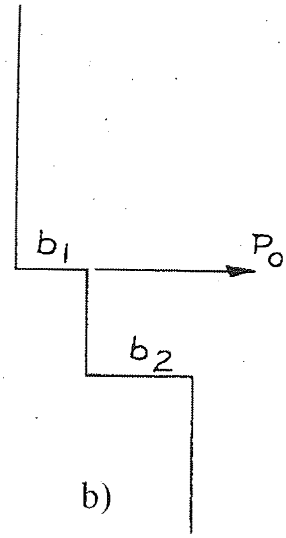
One of the principle features of Winthrop's invention was to reduce the skewing distortion. This is rendering possible by dividing the un-useful area of the lens surface into a plurality of laterally disposed areas (Figure AI.18a). In those areas near the periphery of the lens, the lens is provided with an aspheric surface formed from sections of a figure of revolution such that the principal axes of astigmatism lie in vertical and horizontal planes so that a wearer of the multifocal ophthalmic lens continues to perceive horizontal lines as being horizontal and vertical lines as being vertical and unbroken. However, the height of the ledge, which exists between the various zones, is restricted to a minimum height over the entire width of the lens, which may then be blended during the manufacturing process into the adjacent viewing zones such that the dividing lines between the various viewing zones are rendered invisible. This type of multifocal lens compares to the segment type multifocal available. However, the dividing lines between the various portions of the lens are not visible in the lens according to the present invention as they are in the segment type multifocal lens.

The multifocal lens 100 shown in Fig. AI.18a has an area of constant dioptric focal power for distance 104, an intermediate 106 directly below the distance area 104, and a third area 108 for near vision. The intermediate and nearer areas are divided laterally into three areas. The central area ABB'A' is centered on the principal vertical meridional line 102 and is comprised of two constant dioptric focal power areas obeying the power law shown in Fig. AI.18b. Adjacent to the area ABB'A' are blend areas ACDB and A'C'D'B' so that the peripheral zones CDE and C'D'E' are corrected for skew distortion. In these peripheral areas of the intermediate and near vision zones, the amount of horizontal prism is constant. The principle advantage arising from the correction of skew distortion is the reduction of the height of the horizontal ledges. The ledges are not removed entirely but the height that remains can be rendered cosmetically invisible by use of the sagging method of manufacture. Figure AI.18c. Shows the area of blend produced by the sagging method of manufacture making the height of the ledge cosmetically invisible (about 14 mm).

Also such a lens overcomes the difficulty of having narrow central corridor of clear vision in progressive addition lenses. This happens by combining the progressive power variation and finite power discontinuities at either or both of the boundaries of the intermediate area. Figure AI.18d represent alternative progressive power laws incorporating such discontinuities.



a)



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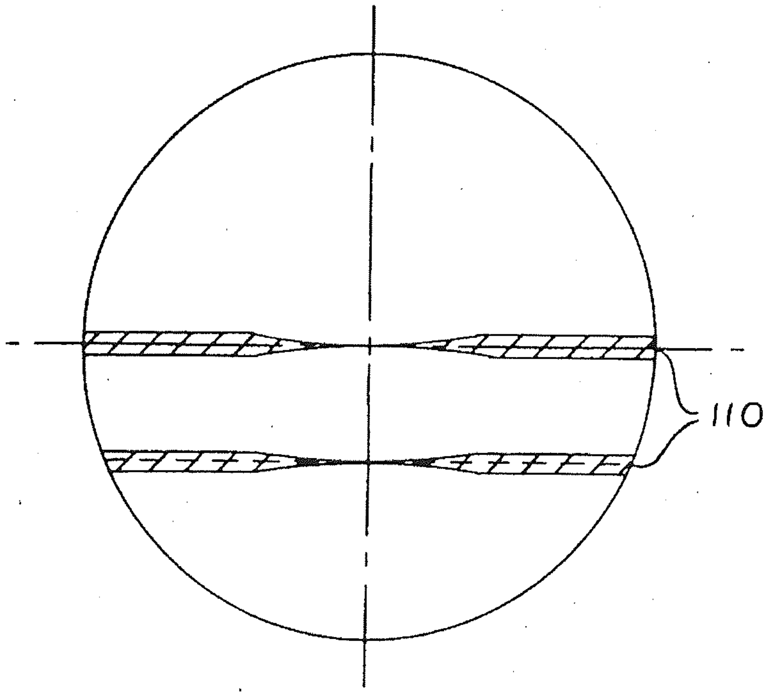

c)

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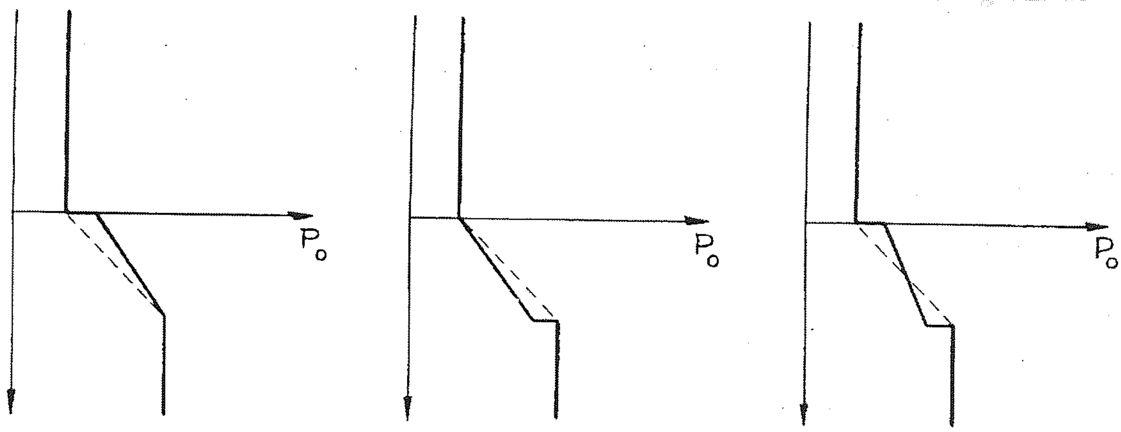


Figure AI.18. *Winthorp's lens. a) A front elevation view of the progressive power ophthalmic lens whose intermediate and near vision portions are divided laterally into a plurality of areas, the outermost of which are totally corrected for skew distortion. b) A diagram showing the power variation of such an ophthalmic lens. c) The area of blend produced by the sagging process, for lens 1.00. d) Are diagrams showing alternative progressive power laws incorporating discontinuities for providing such a lens. (After Winthorp, 1977)*

From the above it is indicated that the power law discontinuities have the effect of reducing the rate of addition of dioptric focal power across the intermediate viewing zone. The evident of such effect is that the corridor of clear vision in the intermediate area is appreciably widened. If the power discontinuities have magnitudes b_1 and b_2, then the astigmatism inside the intermediate area will be given by

$$\mathbf{A = 2\ (B\text{-}b_1\ \text{-}b_2)/h)}\ |\,\mathbf{y}\,|$$

B is the addition of power, **h** is the intermediate area height, |**y**| is a distance from the meridional line, $\mathbf{b_1}$ and $\mathbf{b_2}$ are the values of the power discontinuity steps, where

$$\mathbf{B = b_1 + b_2.}$$

In case of B is 2.0D, h equals 10mm, and b_1 and b_2 equal 0.5D each, then the width w of the corridor of clear vision (area having less than one dioptre of astigmatism) becomes wider (10mm) compared with previous types of progressive continuous power law, where there is no discontinuity (5mm).

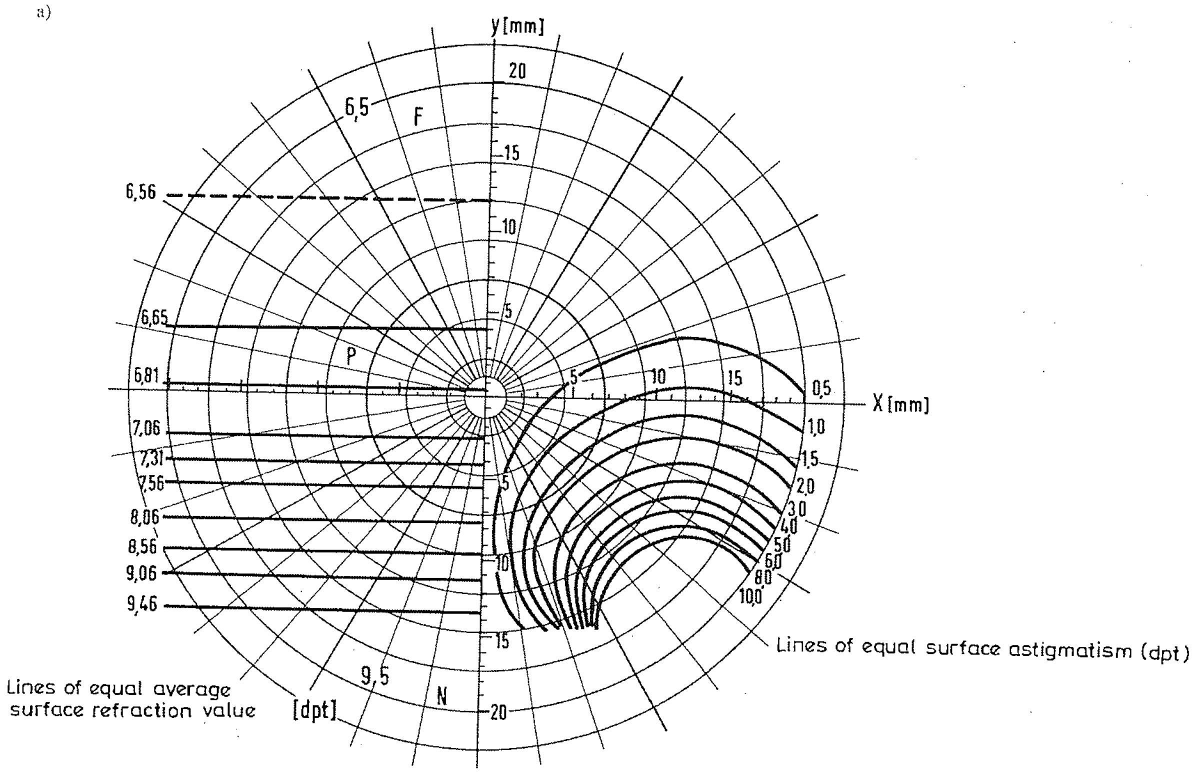
In 1980 *Guilino et al (1980)* described a progressive ophthalmic lens, which was basically characterized as a **hard** lens design. The principal meridian of progression is not actually an umbilical one, having a difference between the two main curvatures which is smaller or equal to $0.12/(n-1)100\ cm^{-1}$. In such a lens the far and near vision zones are widened considerably.

The lines of equal average surface refraction value in the progression zone intersect the main meridian and extend on both ends to the periphery of the eyeglass lens. According to the Minkwitz theorem, in an umbilic surface the surface refraction value D should increase, along the umbilic line and the periphery of the surface, uniformly and with the same gradient. Unfortunately, this produces next to the umbilical line surface astigmatism ΔD, which increases 2 times the surface refraction value.

Also in such a lens the principal meridian of progression is inclined at an angle of 10° nasally in order to simulate the natural binocular vision for near. Figures AI.19a, b show the spread of astigmatism and the average refractive value along the lens surface, according to two embodiments.

Also, Figure AI.19c, d show how the progression power evolves through the lens surface. As can be seen, the maximum value of curvature change along the principal meridian is at the centre of the progression zone at a position about 0.5 x the addition (Fig. AI.19c) while the maximum value of curvature change along the principal meridian is at the end of the progression zone at a position about 0.6 x the addition.

a)


y [mm]
20
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10
5
6,5
F
P
N
9,5
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6,65
6,81
7,06
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7,56
8,06
8,56
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9,46
X [mm]
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2,0
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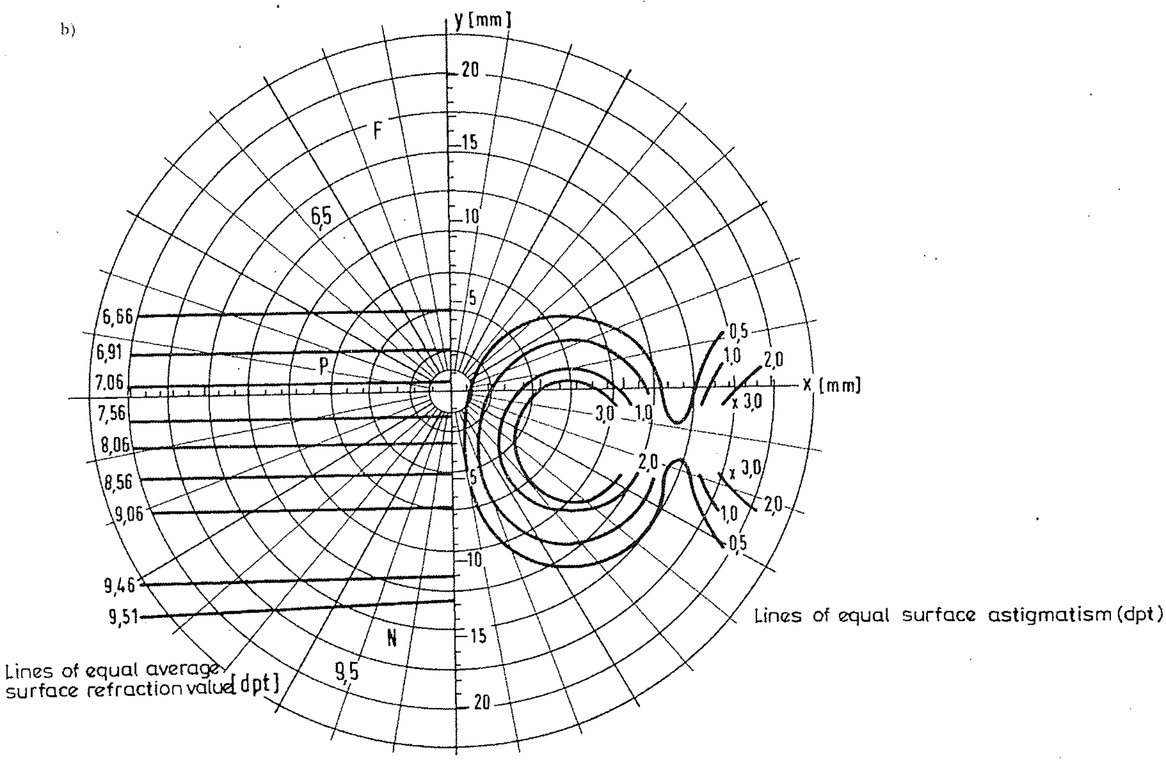
Lines of equal average surface refraction value [dpt]
Lines of equal surface astigmatism (dpt)

b)


y [mm]
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8,06
8,56
9,06
9,46
9,51
X [mm]
0,5
1,0
2,0
3,0
Lines of equal average surface refraction value [dpt]
Lines of equal surface astigmatism (dpt)

Figure AI.19. *Guilino et al progressive ophthalmic lens. a) and b) show lines of equal average surface refraction value (in dioptres) and lines of equal surface astigmatism (in dioptres). c) And d) shows the progression of power through the principal meridian. (From Guilino et al, 1980)*

Maitenaz (1981), for Essilor International introduced a method of producing a surface with a progressive variable power, different to what so far he had done. He chose from a family of surfaces S_1, which had predetermined optical characteristics, and from a second family of surfaces S_2, which had other predetermined characteristics, the best from each family surfaces S_1 and S_2, The surface S_1 selected from the first family were combined with the surface S_2 and their curves of intersection C and D were determined. The surfaces S_1 and S_2 were selected so that their curves C and D provide a corridor respectively at least 15 and 18 mm wide in the intermediate vision zone Z_2' and in the near vision zone Z_3'.

Figure AI.20a shows the surface S_1 selected and the law of progression for such a surface. The main meridian M_1M_1' is an umbilical line having the vertical and horizontal radii of curvature equal. With such a surface the astigmatic aberrations are concentrated in the outer lateral areas of the intermediate zone. Figure AI.20b shows the surface S_2 and the law of progression for such a surface. The main meridian M_1M_1' is not an umbilic curve. This surface S_2 present a vertical prismatic effect with substantially constant value. The combination of the above surfaces S_1 and S_2 produces a lens with a wide corridor and a constant vertical prismatic effect, which means no oblique distortion. (Figure AI.20c) On the progression surface $S = S_1 + S_2$ the plane of the principal meridian M1M1' is a plane of symmetry.

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Figure AI.20. *Maitenaz progressive ophthalmic lens. a) Is a front view showing a surface S_1, used for constructing the final lens, and the law of progression for such a surface (umbilic line). b) Is a front view showing a surface S_2, used for constructing the final lens, and the law of progression for such a surface (non-umbilic line). c) Is a front view of the lens produced by the combination S_1 and S_2, and a chart showing the distribution of the astigmatism aberrations for such a surface. (From Maitenaz, 1981)*

Davenport (1981) on behalf of Younger Manufacturing Company in June 23, 1981 proposed a progressive ophthalmic lens where the intermediate and near zones are uniquely configured in such a way that astigmatism and distortion is limited to less commonly used areas. The design is symmetrical to the principal meridian (x,x), where the curvature is an umbilical one and is characterized by the expression

$$1/R = dx^2/dy^2 [\, 1 + (dx/dy)^2 \,]^{-3/2}$$

Where R is the radius of curvature and x,y are coordinates of the lens surface. It is actually a hard lens design, having constant power at the distance and near vision areas, while the intermediate vision zone, and is generated by portions of a family of circles. These circles are produced by passing an inclined plane through a multiplicity of spheres with known radius, defining the principal meridian (x,x).

Figure AI.21a shows the configuration of the progressive surface related to coordinates x,y. The upper section of the lens and the lower pie-shaped are areas with no distortion. Figure AI.21b shows the law of progression for such a lens. Figure AI.21c shows the power across the lens surface where the grey shaped area is un-useful to the wearer.

Davenport's idea was to provide a progressive power ophthalmic lens in which astigmatism and distortion in the peripheral areas of the lens is significantly decreased. The areas of the intermediate, the far distance and near distance vision zones were uniquely configured and strategically located in order to reduce blur or distortion

x

Figure AI.21. *Davenport's ophthalmic progressive power lens. a) Front view of the progressive power ophthalmic lens illustrating the configuration and location of the distant vision, intermediate vision and near vision viewing zones. B) The progression law of the principal curve of such a lens c) A diagram giving power coordinates in dioptres on a 2 add lens. (From Davenport, 1981).*

Kitchen et al (1981) in December 29, 1981 introduced a progressive power lens. It was a lens similar to the one introduced by Davenport, only the near vision portion had a different configuration. Although he claims that the principal meridian is of the umbilical type, actually in the progression corridor there is not entirely free of astigmatism. The lens had at the top of the progression corridor an astigmatism that was about 20% of the add power, while at the end the astigmatism power was zero. The vertical curvature had lower dioptric power than the horizontal at the top of the progression in such design.

Kitchen claimed that, wearers could easily tolerate the astigmatism, presented at the top of the progression corridor, because this part of the corridor is actually seldom used due to the residual accommodative power. Figure AI.22a shows the various portions of the lens, which actually had no lines or discontinuities. The plane of the principal meridian is a plane of symmetry. Figure AI.22b shows the geometry of such a lens, which is defined in parametric form. The central area between $-y_l$ and $+y_l$ is defined by the expression $Z_{m(x,y)}$ while the peripheral area by the expression $Z_{n(x,y)}$.

$$\mathbf{Z_{m(x,y)} = Z_{mo(x)} + 1/B_{(x)}[(\sqrt{\rho^2_{(x)} + B_{(x)}y^2}) - \rho_{(x)}] - 1/n_{(x)}\ C_{(x)}y^{n}_{(x)}}$$

and

$$\mathbf{Z_{n(x,y)} = Z_{no(x)} + R_{\rho(x)} - \sqrt{R^2_{\rho(x)} - y^2}}$$

$Z_{mo}(x)$ is the expression that describes the geometry of the umbilical line, $B_{(x)}$ is the conic constant of the conic curves consisting the progressive corridor, $\rho_{(x)}$ is the y,z component of local radius of curvature $R_{m(x)}$ of the umbilical line, $C_{(x)}$ is a very small parameter, $n_{(x)}$ is the parameter responsible for the smooth connection of the curve $Z_{m(x,y)}$ to the curve $Z_{n(x,y)}$,

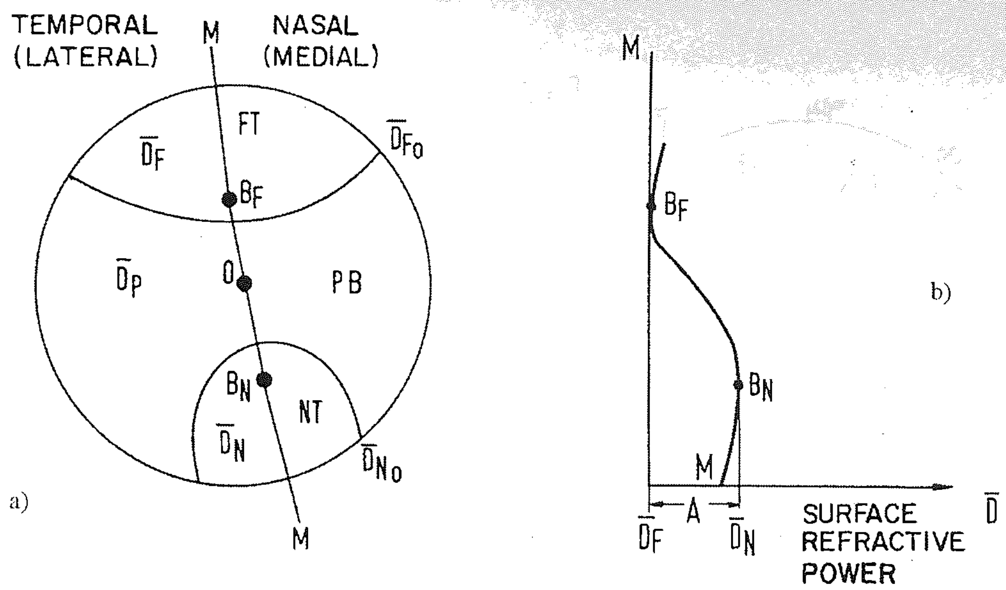
With such a design it is possible to minimize astigmatism in the lower section of the temporal peripheral zone and reduce distortion of horizontal and vertical lines. Also a design with such geometry allows the lens to rotate in order to follow the convergence of the right and left eye without loosing the advantages mentioned above.

Figure AI.22. *Kitchen et al progressive addition ophthalmic lens. a) Schematically illustrates the various areas progressive power lens. b) A description of the half lower section of the lens with its parametric form. (From Kitchen, 1981).*

Guilino, et al. (1982) for Rodenstock proposed a progressive lens, where the front surface had a principal meridian M, which formed an umbilical point line and was curved so that to follow the convergence of the right and left eye when looking for near. Figure AI.23a shows the lens front surface divided into three portions. The upper portion FT (for a line of constant average power DF0 limits distance vision while the lower portion is limited by a line again of constant average power D_{N0}. The centre B_F of area FT is located 6 mm above the geometrical centre of the lens (0) while the centre B_N of area NT is located 12 mm below point (0). This indicates that the length of the progression corridor is 18 mm. The surface had the plane of the principal meridian M as a plane of symmetry. Figure AI.23b shows the law of progression for such a design along the principal meridian M, while the curvature of the principal meridian M fits the equation

$$\mathbf{F(y) = A[1 - (1+e^{-c(y+d)})^{-m}]}$$

Where $A = D_N - D_F$ and the numbers c, d, m are chosen so that the far and near centres B_F and B_N are located as mentioned above relatively to centre (0). In such a design, which is a soft lens design, the far and near vision areas have constant almost spherical power (D_F and $D_N \leq 0.12$ D) and the peripheral astigmatism at the intermediate zone PB is relatively small. According to Guilino wearers can tolerate a surface astigmatism up to 0.50 D. Figure AI.23c compares the above lens design relatively to surface astigmatism with other three brand-name lens designs.



TEMPORAL
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SURFACE
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SURFACE ASTIGMATISM ΔD BETWEEN 0.5 AND 1.5 DPT
" " " " 1.5 AND 3.0 DPT
" " " " 3.0 AND 5.0 DPT
" " " OVER 5.0 DPT

Figure AI.23. *Guilino, et al. progressive power ophthalmic lens. a) Is a diagram illustrating the lens surface divided by the main meridian M into temporal and nasal sections. b) Is a graph illustrating the power law of progression along the principal meridian M. c) are diagrams of the surface iso-astigmatic lines for previous designs compared with the new one invented. (From Guilino, 1982)*

Rupp (1982) for Camelot Industries Corporation, proposed a method for manufacturing a glass lens having a spherical distance portion and an aspherical progressive portion. These lenses were manufactured by using a vacuum forming technique. A lens blank, made of glass, was placed upon a forming block with the concave surface of the blank resting upon the block. Then it was heated to soften, and a vacuum force is applied to cause the blank to sag against the forming block in order to assume the desired progressive surface shape after cooling

van Ligten (1982) had a different approach. He introduced a progressive power lens having a top portion for distance vision and a bottom portion for near vision. The intermediate zone consisted of two vertical lines 13 and 15 as shown in Figure AI.24., which were umbilical lines spaced apart so that each line can be regarded as being constituted of an infinite number of spheres graduated from the sphere 7 (distance vision area) to the sphere 9 (near vision area). The area between lines 13 and 15 is aspheric but astigmatism did not take values more than 0.50 D, which is a tolerate value. The areas between lines 13-17 and 15-19 had also low power astigmatic aberrations. Areas 21 and 23 presented astigmatic aberration but according to van Ligten these are un-usable areas by the wearer. As van Ligten claims the corridor defined by the lines 17 and 19 is approximately 2.5 times wider than the corridor of typical progressive lenses having an umbilical principal meridian

Figure AI.24. *van Ligten's progressive power ophthalmic lens having wide transition corridor 17-19 where astigmatism is less than 0.50 D. (From van Ligten)*

Davenport, et al. (1983) again for Younger Manufacturing Company proposed a theoretical method for making progressive ophthalmic lens having an x, y and z-axis with progressive varying focal length. The curvature of the meridional curve expressed in x,y coordinates was the same with patent *US 4,274,717*. The design was a symmetrical design about the principal meridian.

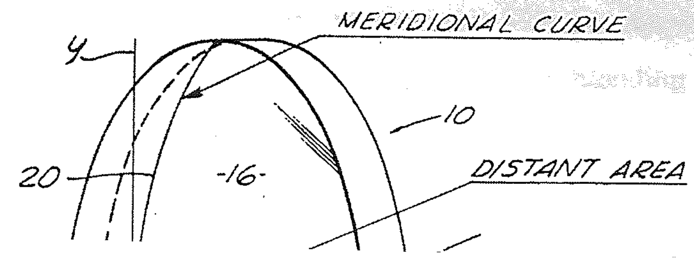
Calculation of the exact contour of the meridional curve was produced for four examples having

a) Constant power at distant –vision area and linear progression from the vertex of the lens surface to the bottom of the lens,
b) Constant distance and near-vision power and linear progression at the intermediate area,
c) Constant power for distance-vision area and parabolic progression through the intermediate and near areas,
d) Constant power for distance and near-vision area and parabolic progression through the intermediate area.

It was a theoretical approach of progressive addition lenses with a lot of mathematics about the principal meridian of the lens.

Figure AI.25b shows the power distribution along the principal meridian for example (b). It is seen from the diagram that the progression zone L starts at the geometrical centre of the lens and extends for 10 mm below it. This is for a lens having a 2 add.

a)



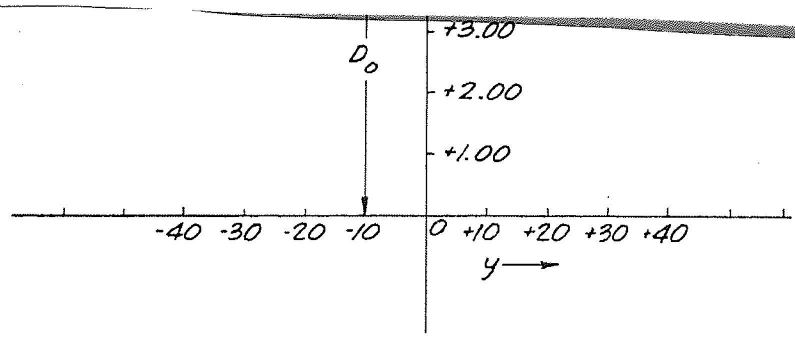


Figure AI.25. *Davenport, et al. ophthalmic progressive power. a) Is diagram of the progressive power lens illustrating the configuration and location of the meridional curve, and the distant and near vision area. b) Is a diagram illustrating the power distribution along the meridional curve (From Davenport, 1983)*

van Ligten, et al. (1984) on behalf of Polycore Optical Pte. Ltd again proposed a progressive power lens similar to his previous one in US Patent *4,362,368*. His lens was a symmetrical progressive addition lens with a wide corridor in the progression zone. Also there is claimed to be an improved balance between astigmatism and distortion in the peripheral areas of the progression. This is achieved by employing a novel formulation of the progression corridor and a blending of the transition corridor with the peripheral area, using a cosine function.

The advantage of using a cosine function in blending the transition corridor with the peripheral area is that closer to the eye's centre of the field of view the distortion becomes rapidly small. As long as the amplitude of the distortion is kept within limits of human tolerance, the total field can be considered optimum. This feature gives the wearer a feeling as if there were no distortion at all, and enhances the dynamic use of the lens. Van Ligten provides also the mathematics and the calculations for such a central corridor wherein the power varies in it and merges smoothly into the distance and reading portions. Figure AI.26 shows the configuration of the lens areas.

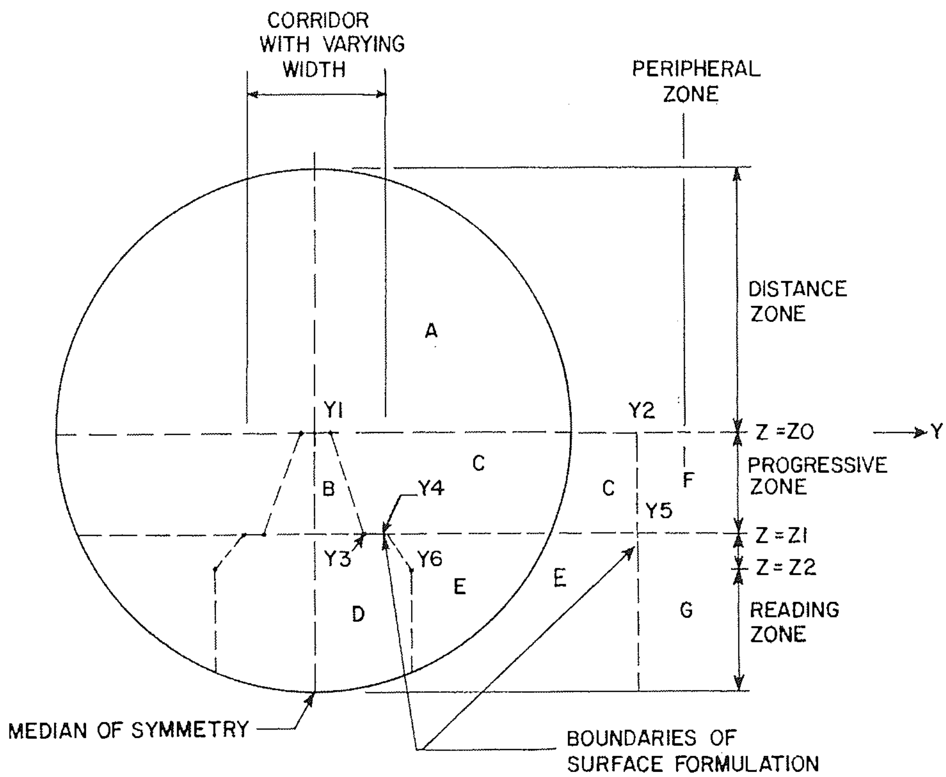


Figure AI.26. *The front surface of the lens and the way it is divided into the various zones. (From van Ligten, 1984)*

Legendre (1984) for Essilor had a different approach on the design of progressive addition lenses. He introduced an ophthalmic lens resembling a bifocal lens of the fused or solid type with an intermediate zone of progression. The transition from the distance to near vision is distributed between a progressively variable power zone and an additional segment superposed thereon. Due to this progression zone the added power is relatively small and therefore the lateral zones only have minor aberrations.

Although an additional segment is employed, the discontinuity of power at the upper boundary is relatively moderate, and therefore the jump is relatively smooth without annoying the user. Figure AI.27., show such a lens with 21 being the progression zone.

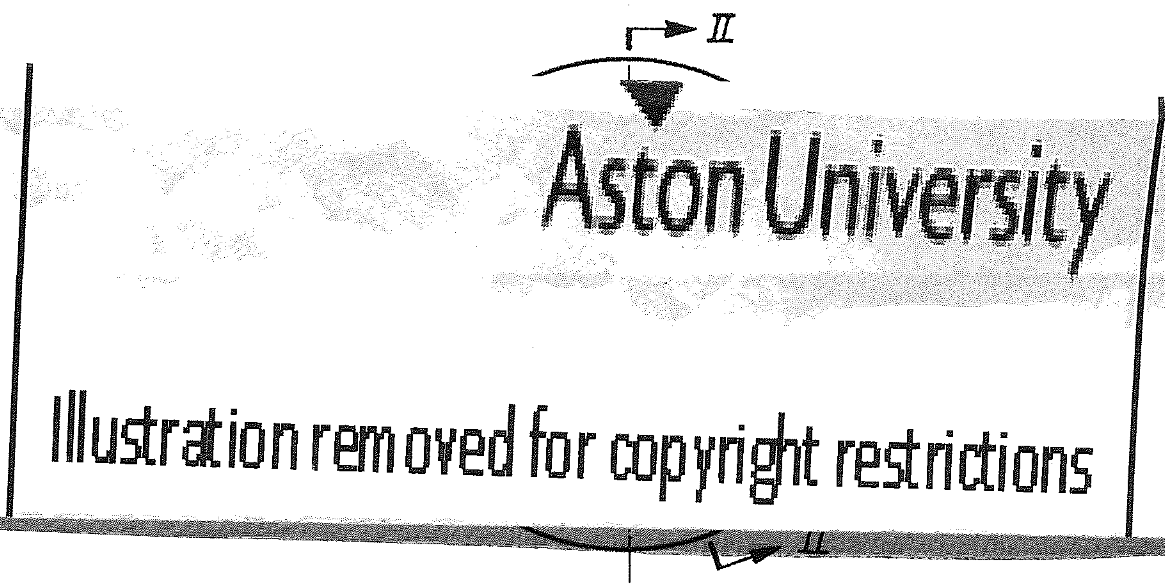


Figure AI.27. *Legendre's progressive lens. It shows a front view of the progressive ophthalmic lens having a near segment 15 and a progressive power zone 21. (From Legendre 1984,)*

Kitani (1984) for Kabushiki Kaisha Hoya Lens proposed a progressive multi-focal lens, in which there is still the same arrangement to prior art lenses, of a spherical distant vision zone, a spherical progressive zone comprising a spherical smooth progressive series, increasing in refractive power and a spherical near vision zone.

The difference of this lens to prior art lenses is that the side areas of the intermediate zone are formed by spherical surfaces, where the refractive powers is the arithmetic mean of those of the distance and near vision areas. At the demarcation area between the side spherical surface (left and right) and the progressive and near zones this continuous surface is smoothly curved so as to minimize distortion.

This design is a symmetrical one related to the main meridian of progression. Figure AI.28 shows the front view of the progressive surface where O' is the geometrical centre of the lens, (8) is the distance zone, (10) and (9) are the progression and near zones respectively. Points L, M, N are specific points on the lens surface. L is 8 mm away from the principal meridian horizontally and 15 mm below the geometrical centre O'. M is 8 mm away from the principal meridian horizontally and 5 mm below the geometrical centre O'. N is 18 mm away from the principal meridian horizontally from the geometrical centre O'. These three points are on the demarcation line

Figure AI.28. *Kitani's Progressive multi-focal lenses, a) is a front view of the progressive lens showing the lines of demarcation of the various zones. (From Kitani, 1984)*

Shinohara, et al. (1985) on behalf of Kabushiki Kaisha Suwa Seikosha made experiments on several designs for optimal vision in conditions such as driving, shopping, and sports activities. In the lens design series produced the qualities of both dynamic and static vision are kept equally high in the distance and intermediate vision areas, while the width of the near vision area is kept at a minimum acceptable value. The requirement for the distance vision zone was that even when the wearer watches an object to the side without moving his head, the blurring, distortion and shaking of images are not produced. In the intermediate zone, it is required that the width of the region through which the image is viewed without blurring is large and the distortion and shaking of images are small in the lateral portions. All the above come to a n expense of the required width of the near vision zone. This zone is reduced to its minimum acceptable value in order to improve the characteristics of the distance and intermediate zones.

In such series of lenses studied, the principal curvatures C1 and C2 at each arbitrary point on the principal meridian in the intermediate vision zone satisfied the condition:

$$|C1-C2| \leq 1/(N-1)(m^{-1}).$$

while in the near vision zone satisfied the conditions:

$$|C1-C2| \leq 1/(N-1)(m^{-1}).$$

$$\frac{D2-0.5}{N-1} \leq \frac{C1+C2}{2} \leq \frac{D2+0.5}{N-1} \; (m^{-1})$$

where N is the refractive index of the lens material.

The minimum width of the intermediate vision zone and the maximum width of the near vision zone are S (mm) and W (mm) respectively. The minimum width S and the maximum width W satisfied the conditions:

$$W \leq 30/A \text{ (mm)}$$
$$W \leq 1.5 \times S \text{ (mm)},$$

where A is the value of the additional power expressed in dioptres.

The gradient of the progressive power at each arbitrary point along the principal meridian curve is G (dioptre/mm). Every point along the principal meridian curve in the intermediate vision zone satisfied the condition:

$$G \leq A/18 \text{ (dioptre/mm)},$$

where A is the additional power in dioptres.

The length L of the progression zone according to Shinohara et al should be at least 18 mm in order to have according to the studies carried out a width of progression of about 9 mm.

According to the studies carried out the maximum acceptable value of astigmatism is about 1 D, but the mean power for the distance and near zone should not exceed ± 0.50 D difference from the desired. These series of lenses all have an umbilical principal meridian and the progressive surface was made either symmetrical or asymmetrical related to this meridian, which inclined nasally to adapt for convergence.

Figure AI.29. *Shinohara, et al. Progressive multifocal ophthalmic lens. a),b),c),d) show the distribution of astigmatism of different embodiments of the progressive addition lens produced. (From Shinohara, 1985).*

Shinohara (1986) again for Kabushiki Kaisha Suwa Seikosha provided again a series of improved progressive lenses, where there is a balance between the lens characteristics of static vision and that of dynamic vision. This balance is obtainable by selecting and combining elements for each of the three zones of the lens, the far zone, the near zone and the intermediate zone, the law of the rate of change of curvature along the principal meridian curve and the formation of a spherical surface or an aspherical surface in the far zone and the near zone.

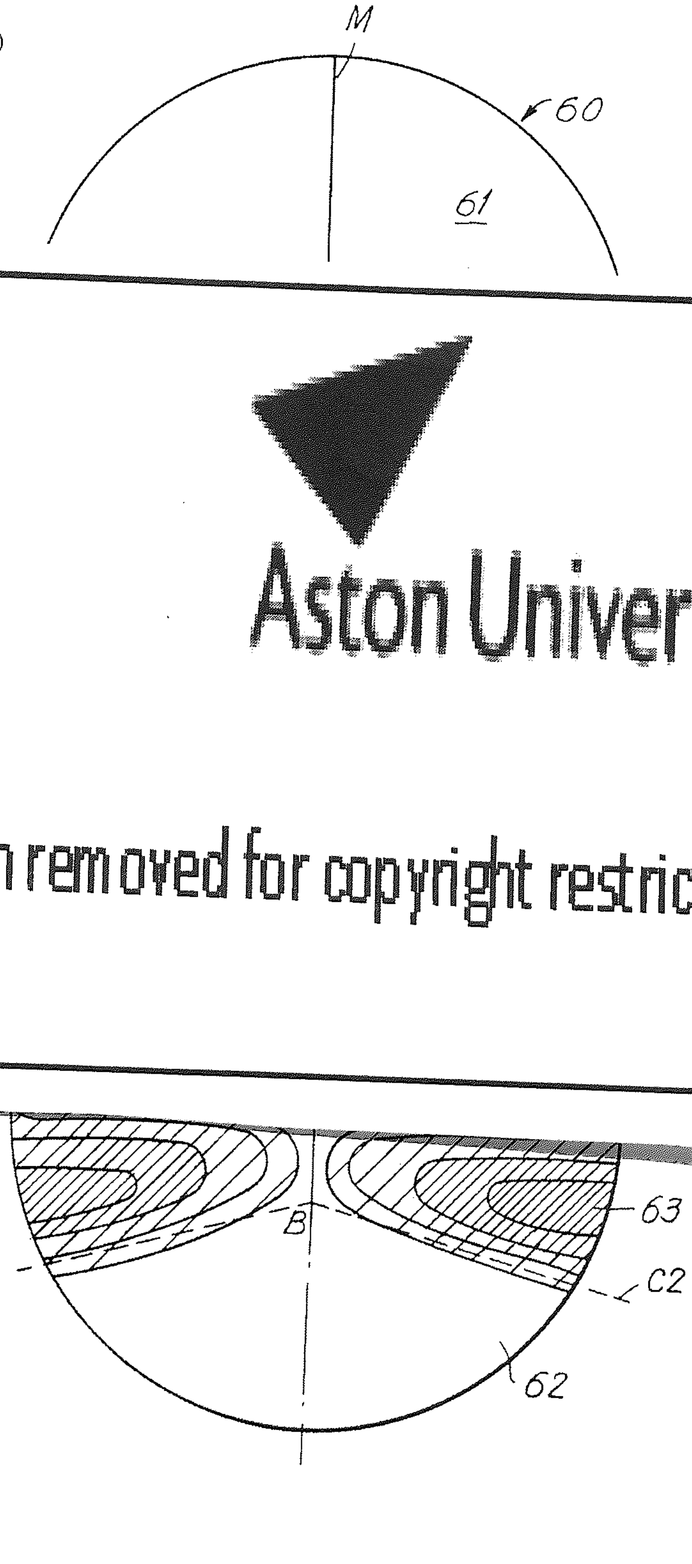
In this patent he gives information about the normal and skew distortion perceived by the user of progressive lenses and how distortion and astigmatism are related to static and dynamic vision. The structure of the front progressive addition face of the lens is described in Figure AI.30a. C_1 is the boundary between the distance and the intermediate zones while C_2 is the boundary for intermediate and near. A is the optical centre for distance and B is the optical centre for near. The boundary line C_2 is a straight line, which is inclined downwards, symmetrically with respect to the principal meridian, as it moves away from it.

According to Shinohara astigmatism must not exceed 0.50 D in order to be tolerate by the wearer so the viewing image to be focus properly. He proposed different type of designs depending whether the distance and the near vision zones are spherical or aspheric. Figure AI.30b the astigmatism distribution in such a lens where both distance and near vision zones are spherical.

One of his proposed lenses is seen in Figure AI.30f. In the distance vision zone, there is an area D, which is spherical. This area D extends at least a minimum distance of 2.5 mm from the principal meridian curve on both sides. Outside area D the area D_1 is aspheric, having an increasing horizontal curvature as it becomes more distant from the principal meridian.

In the near vision zone, area E is spherical. This area E extends at least a minimum distance of 1.5 mm from the principal meridian curve on both sides. Outside area E the area E_1 is aspheric, having a decreasing horizontal curvature as it becomes more distant from the principal meridian. With such a design, in the side portions of the distance zone and the near zone, distortion of the image in the peripheral portion is reduced, and the width of the intermediate zone is broadened. The lens is a symmetrical design relative to the principal meridian, which is umbilical.

a)



d)

c)

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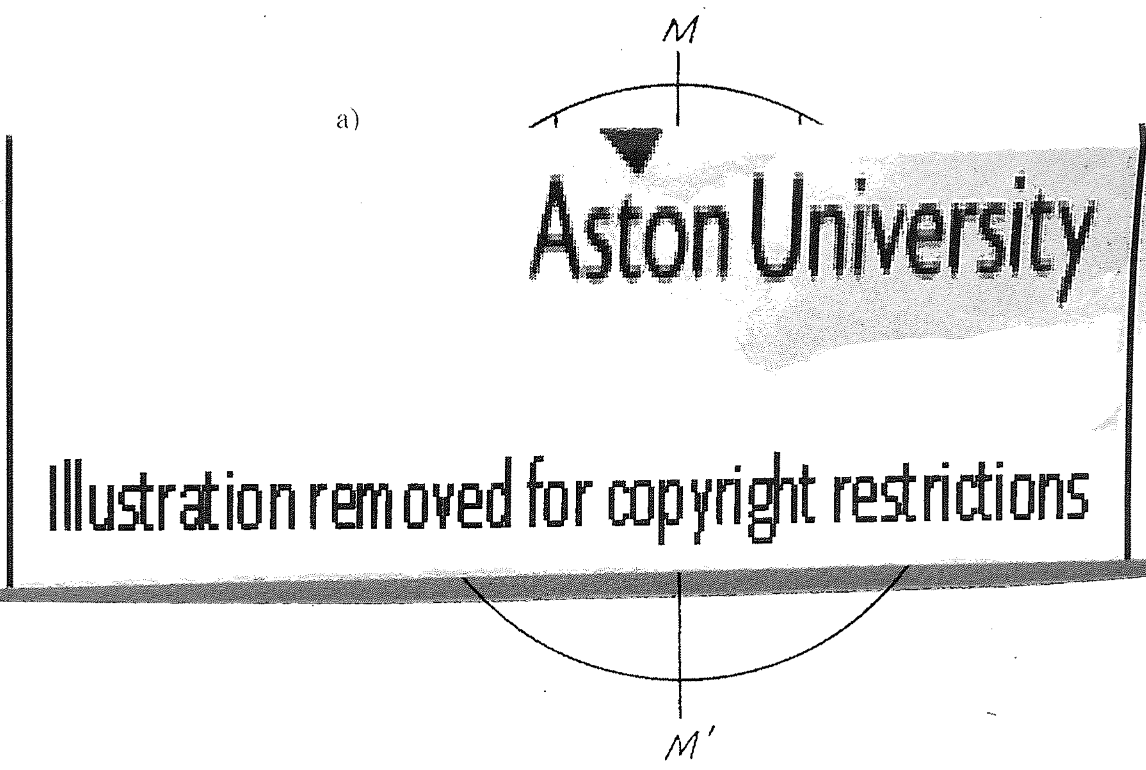
Figure AI.30. *Shinohara's progressive lens. a) Is the construction of the front surface of the lens. b) Is the distribution of astigmatism viewed through the lens of Fig. (a) having spherical distance and near vision zones. c) Is the distribution of astigmatism viewed through a lens with spherical distance and aspherical near zone. d) Is the distribution of astigmatism viewed through a lens with aspherical distance and near zone. e) Is the distribution of astigmatism viewed through a lens with aspherical distance and near zone, while the boundary line C_1 is inclined downwards when moving away from the principal meridian. f) Is the construction of the front surface of an innovative design. g) Is the distribution of astigmatism viewed through such a lens of Figure (f). (From Shinohara, 1986)*

Okazaki et al (1986) proposed an ophthalmic lens having a progressively variable focal power, which as he claims is convenient for "daily use". In each of the distance, intermediate and near zones the concentration of the aberration was reduced in the peripheral portion. The distance zone F was divided horizontally into three areas where the astigmatism was minimum in the central region F_1 and increases in the outer areas F_2 and F_3 on both sides of the principal meridian MM' which was substantially in the centre and it was umbilic at the intermediate zone P. (Figure AI.31a)

The width of the centre area F_1 of the distance zone F was at least 30 mm, which corresponds to the region of rotating the eyes an angle of 30° and is most frequently used. The skew distortion in the outer areas of the intermediate zone P falls within range of from about 0.0003 to 0.0020 when the power addition is in the range of 1 to 3 dioptres. In Figure AI.31b the shaded area of the lens is the region where the astigmatism is large. It should be noted that the value of the astigmatism does not increase rapidly, but increases slowly.

a)



b)

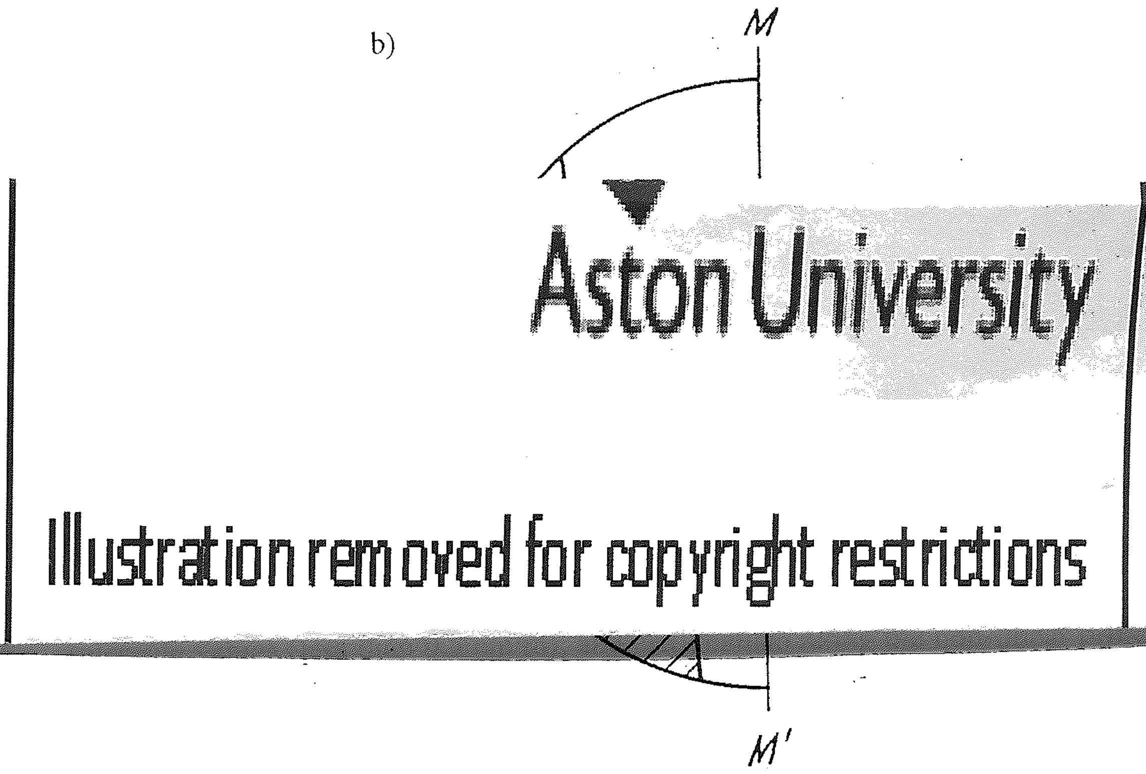


Figure AI.31. *Okazaki's progressive lens. a) Is the construction of the front surface of the lens. b) Is the distribution of astigmatism viewed through the lens of Fig. (a). (From Okazaki, 1986)*

FueGerhard and *Lahres (1986)* on behalf of Carl-Zeiss provided a progressive addition spectacle lens, with a short progressive zone, which substantially satisfies in each zone all monocular and binocular requirements. This innovative design takes into account the sensitivity of the lens wearer to binocularly non-harmonizing directions of sight. Figure AI.32a shows the progressive surface of such a lens. The principal meridian, which in this patent is called the principal sight line follows the accommodation-convergence movement of the eye, is non linear and divides the lens into nasal and temporal portions.

Over the entire lens surface, points having the same horizontal distance from the principal sight line and for the same elevation present approximately the same values of astigmatism and focusing error. Such horizontal symmetry across the entire lens surface contributes in that the lens wearer will see either an equally sharp or an equally blurred image of the object with both eyes; as a result, binocular vision becomes very pleasing.

Figure AI.32b explains diagrammatically what happens when both eyes look through the lens an object P. As a result of the prismatic effects of the spectacle lenses, point P appears for the left eye 7 at position P_L and for the right eye 8 at P_R. The eye-side lines of sight now extend along the lines 14 and 15. The vertical difference in position is designated by $\Delta.P_v$. By dividing ΔP_v with the distance between the lens and the object, the value of the vertical directional error is obtained. The same applies to the horizontal difference ΔP_H. In order to improve this drawback the spline analysis technique is used in order to produce a single surface which is twice continuously differentiable and which conforms to the desired optical properties. This means that the horizontal and vertical direction errors are maintained within tolerable values (less than 0.5 cm/m), and astigmatism along the non-linear principal sight line is held below 0.5 dioptres.

Figure AI.32c show the vertical directional error profiles of a prior art progressive lens characterized by the dashed-line curves for different horizontal sections from point 0. The solid-line curves show the resulting vertical directional error profiles after applying the spline analysis method. Figure AI.32d show the astigmatism distribution of such a progressive surface. The distance zone appears to be large and a relatively large area is present for the near-vision zone, while astigmatism is extremely small in comparison with astigmatism in prior progressive lenses. Figure AI.32e show lines of constant average surface power for the progressive surface of the same lens. It is obvious that the surface power is substantially symmetrical, horizontally related to the principal sight line. In areas lateral to the progressive and near vision zones it reaches a value almost equal to the far vision zone. The transition of the surface power from the far-vision zone to the near-vision zone along the principal sight line is presented having an additional power of 2 dioptres.

a)

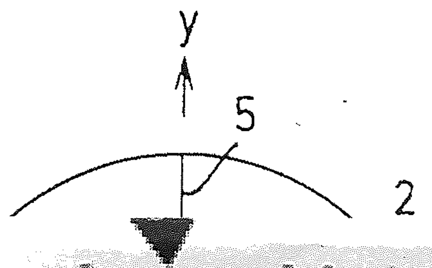


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Figure AI.32. *a) Is the progressive lens with the principal sight line b) is a drawing explaining how binocular vision is disturbed due to vertical and horizontal prismatic effects. c) Is a graph with the values of the vertical directional errors for a prior art progressive lens and for the improved lens with a 60 mm diameter d) is a view showing the distribution of lines of equal astigmatism over the lens surface. e) Is a view showing lines of constant average surface dioptric power over the lens surface. (From FueGerhard, 1986).*

Shinohara (1986) again for Seiko Epson Corporation produced a progressive addition ophthalmic lens, which was improved in chromatic aberration in the near vision area and is thinner and lighter than prior art progressive lenses. These effects take place when a prism is added to the lens, in order to alter the chromatic aberration of the lens. The base of the prism is oriented in the direction of 90° to the lens surface. The amount of prism added to the innovated progressive lens should be in the range of 1 prism D to 6 prisms D in order to be effective.

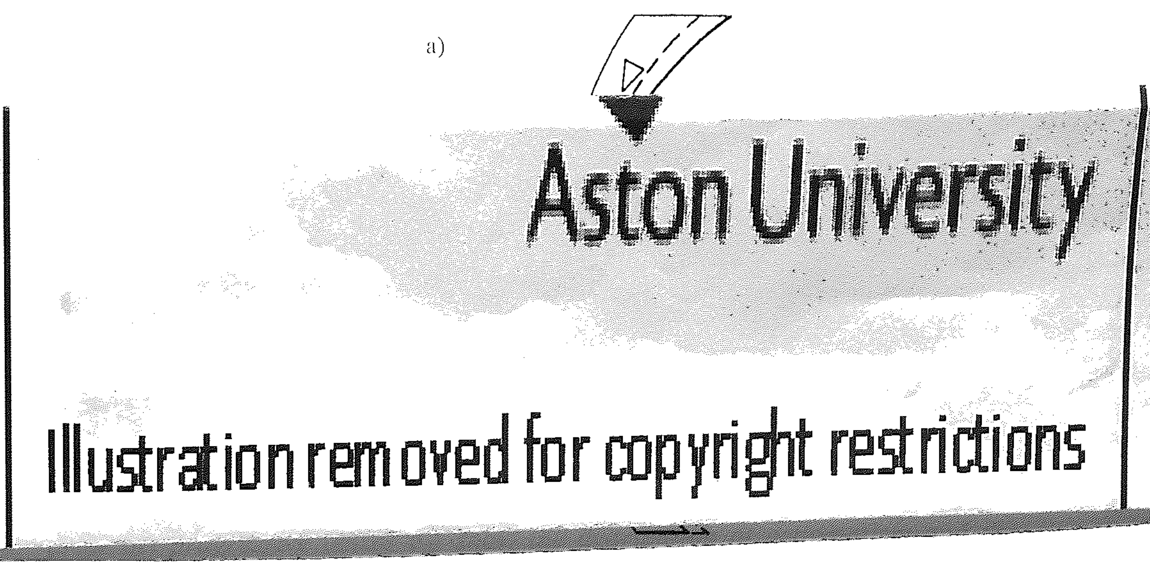
The following relationship is employed to improve the chromatic aberration by the addition of the prism to the lens:

Pt>-k x (PW+ADD)-0.2 x v,

where **1.5<k<2.5,**

"Pt" is the magnitude of the prism, "v" is the Abbe's number of the lens material, "PW" is the power of the lens, and ADD is the additional power. The lens is tinted with a colour consisting of yellow, brown and blue. Also by adding a prism the astigmatic aberration in the near zone is reduced although in the far is increased. In the far zone, by using aspheric surfaces the astigmatism is compensated.

a)



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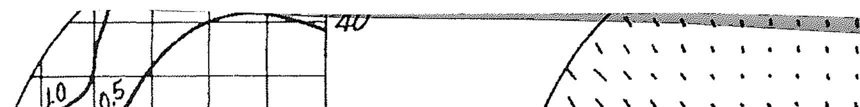

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Figure AI.33. *a) Is a graph illustrating the distribution of prisms and the prism thinning in the near zone. b_1) show the distribution of astigmatism and the direction of astigmatism in prior art progressive lenses b_2) show the distribution of astigmatism and the direction of astigmatism after adding prism progressive lenses. (From Shinohara, 1986)*

Having the same objects with the above patent, *Shinohara (1987)*, for Seiko Epson Kabushiki Kaisha, produced another patent. The factor that plays in this patent an important role is the relationship between the base curve selected for the distance and near zones and the final power of the lens at these points.

The method of the construction of this type of lens, especially when the final power of the lens for distance vision has to correct high myopia or hypermetropia, is related to the astigmatism and distortion presented with respect to the visual angle, which is the angle of the eye's rotation related to the optical axis of the lens. When reading this visual angle in progressive lenses reaches values up to 30 - 40°.

In order to eliminate the above aberrations the principal meridian curve of the invented lens, in contrary to conventional progressive lenses of prior art where it is spherical with ρt=ρs, it is aspherical at the areas of distance and near zones. At the centre points of the distance zone and the near zone, ρt= ρs. The progression corridor is umbilical. At points on the lens, which are more distant from the centre points of both zones upward, downward and toward the peripheral part of the lens, ρt gradually decreases. In the portion above the point 30^0 upward in terms of the visual angle and the portion below the point 50^0 downward in terms of the visual angle, ρt stays constant. The increasing rate of curvature above the centre of the distance zone and that below the centre of the near zone is 0.02D/mm and 0.01D/mm respectfully in terms of the focal power. Such a lens design combined with the right base curve in relation to the focal power of the lens at the distance and near zones gives larger distance and near vision zones where the exhibiting astigmatism is less than 0.50 D. Also the right value base curve in combination with the aspherical surface produces a lens, which is thinner and lighter.

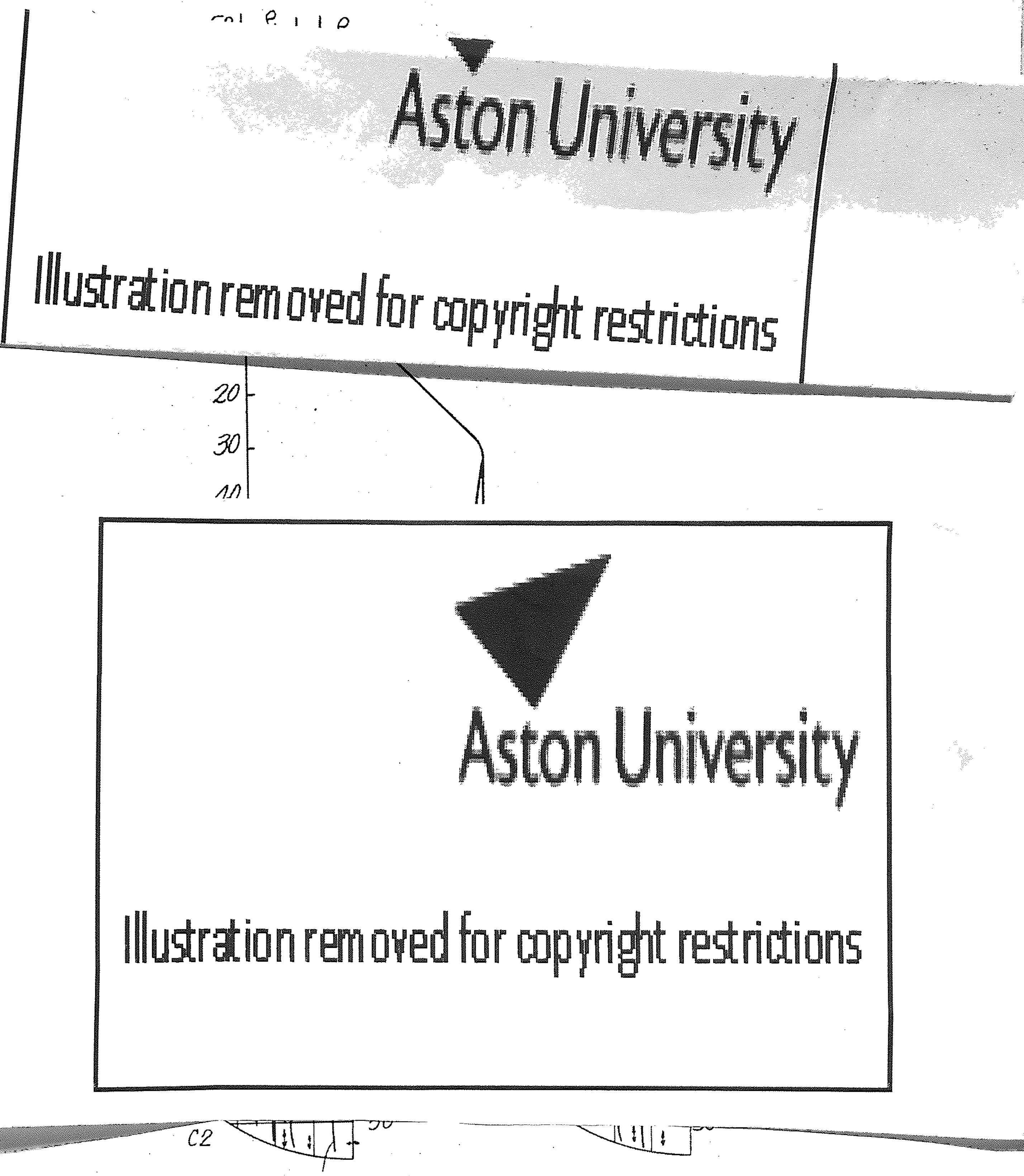

Figure AI.34. *a) Illustrates the change of the curvature at each point on the principal meridian curve into the horizontal and vertical directions (pt and ps) with respect to the principal meridian curve. b) Illustrates the distribution of the astigmatism of a prior art progressive lens c) illustrates the distribution of the astigmatism of the proposed progressive lens. (From Shinohara, 1987)*

Barkan, et al. (1987), for Sola International provided a method for making a progressive lens. In such a method for progressive lens design, where there is a gradual change in optical power from the distance zone to the near zone, the following steps was proposed by Barkan:

a) The creation of a coordinate system to provide the desired solutions

b) The algebraic forms defining the surface at the distance, near and intermediate zones

c) The algebraic form of the boundaries between the three zones.

All the above are analysed by means of ray-tracing in order to permit adjustments for the intermediate and near zones. These adjustments can solve localized excessive astigmatism and distortion. Such a lens design provided according to Barkan acceptably small astigmatism, less than 0.5 D along the eye path, while the eye path deviated from a vertical centreline of the lens in order to follow the natural convergence of the eyes as they move from distance to near vision. In addition, the boundaries 16 and 18 were curved so as to allow the joining of the zones over a great distance and over a large part of the lens. This was selected in order to limit aberrations in the intermediate zone. Figure AI.35 shows the configuration of the progressive front face of the lens and the coordinate system for defining the lens surface.

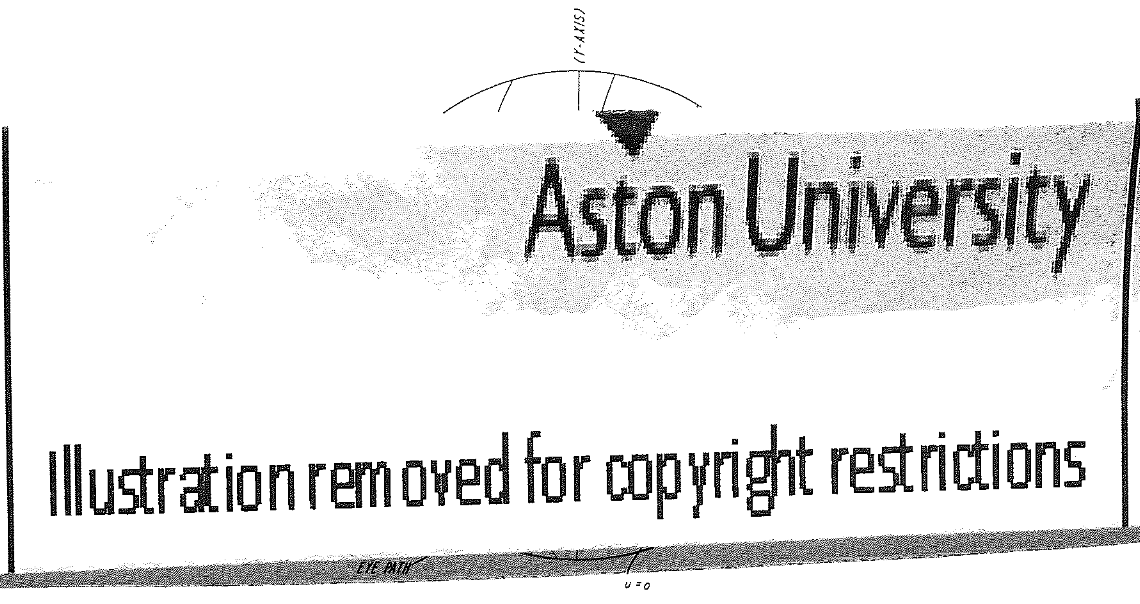

Figure AI.35. *A front view of the progressive lens, illustrating the coordinate system used to define the surface of the lens. (From Barkan, et al., 1987)*

Kitani (1988), for Hoya Corporation introduced a progressive ophthalmic lens with a design that takes into consideration that not only the eyeball but also the head of the wearer is turned towards a visual target located on a lateral side when the wearer looks at such a visual target. In the case of the prior art progressive power ophthalmic lens, the arrangement of the visual target, which was assumed by a designer when he designs a lens, had been unnatural because of the fact that the rotation of the head was not taken into account.

Figure AI.36a shows the relation between the angle of the head and the eyeball in relation to the straightforward gaze. When the wearer turns his eyes toward a target disposed laterally at an angle β, this angle β is achieved by the addition of the angle of rotation of the head β_H and the angle of rotation of the eyeballs β_E. So β is expressed by the relation $\beta = \beta_H + \beta_E$.

In such a design the umbilical principal meridian curve in the intermediate and near zone is displaced nasally dividing the lens into nasal and temporal side sections where the distribution of astigmatism is made asymmetrical to each other section. The progression corridor had 14 mm height and it was inclined nasally 2.5 mm. Figure AI.36c shows how binocular vision is changed when taking into consideration the rotation of the head. Instead of having a straight line D of visual targets when looking at different angles as shown in Fig. AI.36b, the truth is that the visual targets form a curve D'', which is created by the curves D'_L and D'_R form by each eye monocular.

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Figure AI.36. *a) Is a diagram illustrating the relation between the angle of the rotation of the head* β_H *and the angle of the eyeball* β_E *of the spectacle wearer when viewing at an object, c) is a diagram illustrating, the position of a visual target for a wearer before taking into consideration the rotation of his head. c) Is a diagram illustrating, the position of a visual target for a wearer wearing such an ophthalmic lens. (From Kitani, 1987)*

The lens provided by *Shinohara (1988)* for Seiko Epson Corporation, was intended for use in tasks in which the intermediate vision and the near vision are mainly performed, such as writing, medical operations like surgery, working with tools.

In such a design the astigmatism on the central meridional curve is minimized, and is spread in larger area on the distance vision zone. In the distance zone the portion with astigmatism less than 0.50 D is much smaller than the prior art lens but this produces a wide and comfortable visual zone in the intermediate zone reducing in this way the shaking of images in this area.

According to Shinohara a gradient G of the focal power variation between the optical centre of the distance zone and the optical centre of the near zone should satisfy the condition:

$G \leq ADD/20$ (dioptre/mm),

where ADD is the additional power in units of dioptres. The maximum width W (mm) of the clear vision for the distance zone should satisfy the condition:

$5 \leq W \leq 30$ (mm).

Figure AI.37a shows the astigmatic distribution in such a lens design. The optical centre of the distance zone A is 10 mm above the geometrical centre of the lens and 5 mm above the eye position of the wearer. The optical centre of the near distance is 15 mm below the geometrical centre of the lens. In such a lens the ratio of the widths of clear vision for the distance and near zones in relation to the width of the intermediate zone is 2,3 and 1,5 times respectfully.

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Figure AI.37. *It is a diagram depicting the distribution of astigmatism of such a progressive ophthalmic. A is the optical centre for distance and B for near. 0 is the geometrical centre of the lens and W is the width of the clear vision in the three vision zones (From Shinohara, 1988)*

Maitenaz (1988) on behalf of Essilor proposed a new progressive ophthalmic lens, where the main meridian was displaced relative to the vertical plane passing through the optical centre of the lens towards the nose by about 0.8 to 1.33 millimetres. The plane containing the main meridian is at an angle of about 5.5^{0} to 7.5^{0} relatively to the vertical plane, and the main meridian converges towards the nose in the lower part of the lens.

With such a lateral sliding motion of the main meridian, visual comfort can be achieved for intermediate vision and for near vision, without resulting in any excessive reduction of the area of far vision. Figure AI.38 shows the sift of the main meridian.

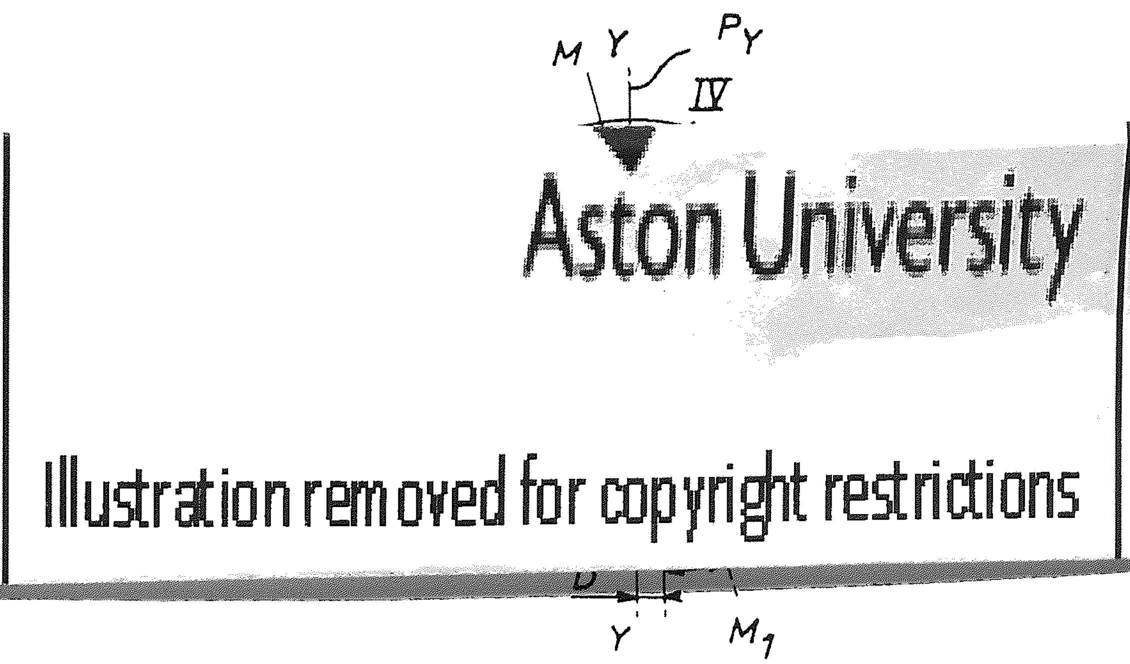

Figure AI.38. *Maitenaz's progressive multifocal lens. It is a front view of a progressive lens where the principal meridian is displaced relatively to the vertical plane passing from the optical centre of the lens (0). (From Maitenaz, 1988)*

Furter (1988) for Carl-Zeiss Company produced a progressive lens in accordance with the mathematical method of spline analysis for use in tasks such as computer-screen work. Such a lens is characterized in that it has two separate progressive zones (5, 6) of continuously varying optical power, which is twice continuously differentiable nasally and temporally at least up to a horizontal viewing angle of substantially 25°.

Figure AI.39a shows the construction of the progressive surface of the lens. Zone (2), which has a semi-rhombus shape, is design for distance vision and has constant surface power. Zones (3) is for intermediate vision and (4) for near vision, both having constant surface power. Zone (5) is progressive variable power area connecting the distance zone (2) with the intermediate zone (3). Zone (6) is progressive variable power area connecting the intermediate zone (3) with the near vision zone (4). Figure AI.39b shows the power variation law of the principal meridian (7) or (8) if the meridian is constructed such to follow the eye convergence situation.

a)

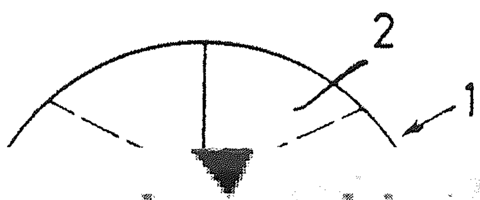

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Figure AI.39. *Furter's multi-focal spectacle lens. a) Is a schematic diagram of the various zones of the lens. b) Is a diagram showing the law of progression along the principal meridian. c) Is a plan view of the progressive lens showing the distribution of astigmatism. d) Is a plan view showing the constant average surface dioptric power. (From Furter, 1988)*

Figure AI.39c shows the spread of astigmatism over the entire progressive surface. It is seen that along the principal meridian astigmatism does not exceed 0.50 D. The value of astigmatism outside the second progressive zone (6) does not exceed 1 to 1.5 times the value of the addition, while outside the first progressive zone (5) does not exceed 3 times the value of the addition. Along the principal meridian (7), which provides a horizontal symmetry on the lens surface, the power varies at a step of 0.15 times the addition.

Dufour, et al (1989) introduced for Essilor a progressive lens, which had the same concept as the one introduced by Furter. The lens was intended for use for specific tasks such computer work.

As Figure AI.40a shows the areas of constant distant, intermediate and near vision are respectfully VL, VI and VP. Between areas VL and VI and VI and VP the surface power progressively varies in order to smoothly connect this three constant power zones. A_1, A_2, A_3 and A_4 are points on the principal meridian and at the boundaries of the zones with constant power.

Related to the geometrical centre of the lens these points are, A_1 15 mm above it, A_2 4mm above it, A_3 7mm below it and A_4 15mm below it. The principal meridian, which is a plane of symmetry for this lens, present astigmatism lower then 0, 12 D. As it is seen from Figure AI.40c astigmatism is concentrated in lateral areas of the second progression and near zone VP, but does not exceed the values of the addition.

Y (mm)

a)

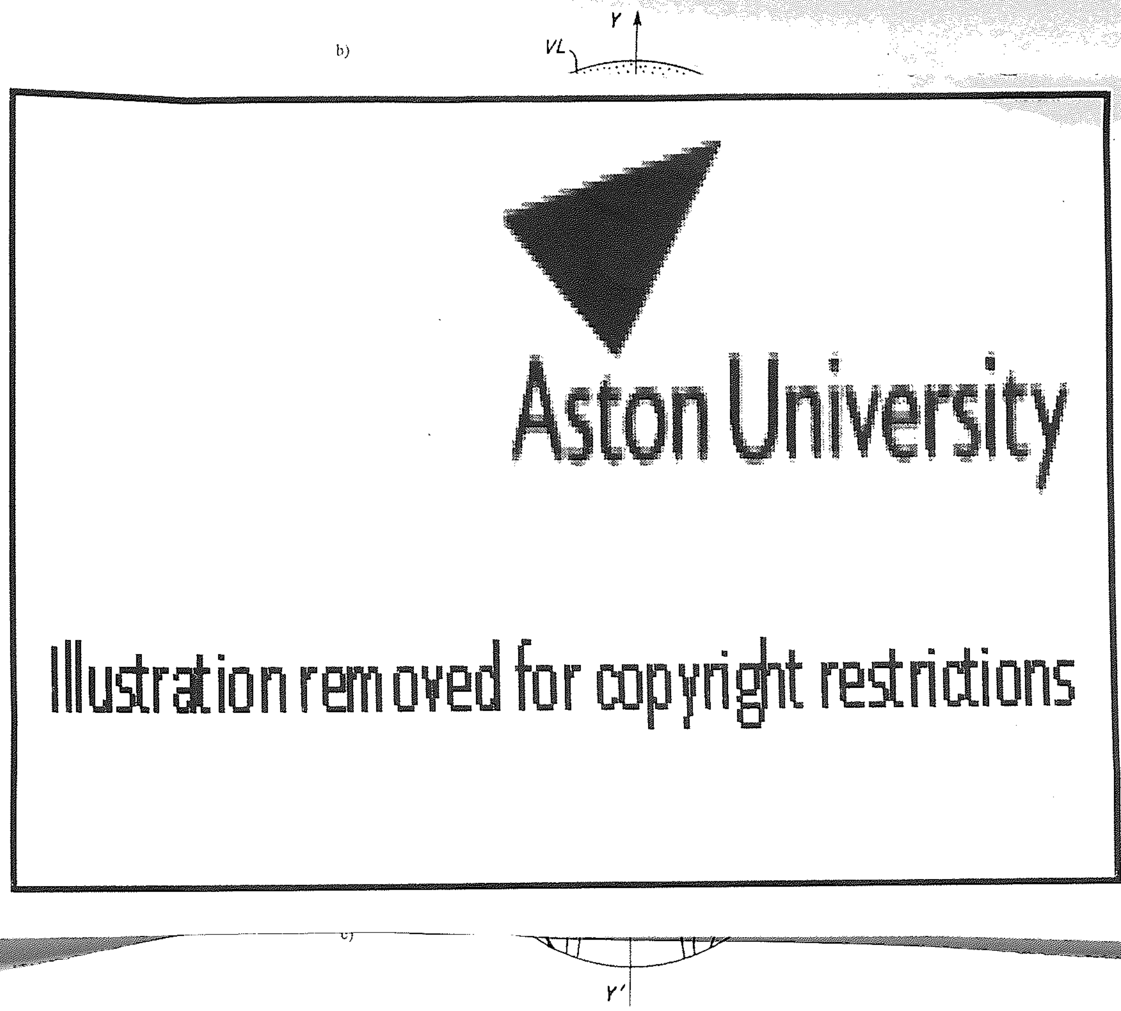

Figure AI.40. *Dufour, et al, progressive lens. a) Is a graph showing the variation of power along the principal progression meridian of the lens. b) Shows the lens front view and the areas of constant power VL, VI, and VP. c) Shows curves of equal surface astigmatism on the lens front face. (From Dufour, 1989)*

Ewer (1989) for Pilkington Vision care provided a type of bifocal lens having a near segment, which incorporates an intermediate vision zone with progressive power characteristics. This visible segment had a boundary where an abrupt change in power was present having a dioptric power which was ranging between 0, 50 D to 0, 50 D less than the addition. After the boundary the rate of change of power in the intermediate zone of progressively increasing power was between 0.03 to 0.25 dioptres/mm. Figure AI.41 shows such a lens with (1) being the distance vision zone (5) the boundary (3) the intermediate zone of progression (2) the near zone and (6) the principal meridian. (9) Are the lateral invisible boundaries of the progression zone.

Figure AI.41. *Ewer's multifocal lens, resembling a flat-top bifocal with (3) in the near segment a progression is incorporated (From Ewer, 1989)*

Dufour (1989) for Essilor provided a different progressive addition ophthalmic lens. So far the designs produced had either a constant length of the progression and an optical power progression gradient, which varied in order to achieve different addition, or a progression length, which linearly increased according to the addition but with a constant gradient of optical power progression. With the two previously mentioned designs the wearer required an adaptation time to get use of his new progressive addition lenses when he changed addition values. The innovative design that Dufour presented required a smaller effort of physiological adaptation and adaptation time when the wearer changed his lenses of a pair of lower addition to a pair of higher one.

Figure AI.42a shows the construction zones of such a lens and the concept of such design. Zones VL, VI, VP are for distance intermediate and near vision areas. The main meridian MP is nearly umbilical (astigmatism < 0.25 D) and is inclined towards the nose. C_1 and C_2 are the boundaries of the three vision zones.

The curvature of the main meridian curve in such a lens begins to vary not at point A_1 at the first boundary C_1 but at a point A_3 having a distance d_1 in-between. Also the progression does not stop at point A_2 at the second boundary C_2 but at a point A_4 in the zone VP. Depending on the increase of the value of the addition these two distances d_1 and d_2 decrease and respectfully the progression length D decreases also.

The difference in addition power due to the continuation of the progression in the near vision zone between points A_2 and A_4 gives an increase of the nominal addition power between points A_1 and A_2. This results in a more comfortable adaptation from the wearer point of view when he changes his pair of lenses to a higher addition one. Table AI.1 shows a numerical example of such a design, which can be classified under the soft design in respect the astigmatic aberration spread.

Table 1

Addition	(diopters)	0,5	1	1,5	2	2,5	3	3,5
$\mathbf{d_1}$	(mm)	4	2,3	1,2	0,5	0,15	0,02	0
$\mathbf{d_2}$	(mm)	10	7,2	5	3,3	2	1,2	1
D	(mm)	26	24,9	23,8	22,8	21,9	21,2	21
A'	(diopters)	1	1,47	1,89	2,23	2,59	3,01	3,5
ΔA	(diopters)	0,5	0,47	0,39	0,23	0,09	0,01	0

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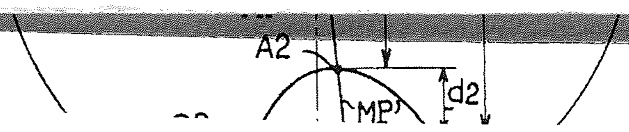

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Figure AI.42. *Dufour's multifocal ophthalmic lens. a) Is a front view showing the construction zones of the lens. b) Shows iso-astigmatism curves of a lens in accordance with the invention having a power addition of 2 dioptres. (From Dufour, 1989)*

Barkan, et al. (1989) for Sola International provided a method for optimizing a progressive lens performance. According to Barkan the important quantitative measures of lens performance are astigmatism, orthoscopy and mean curvature.

The best way of computing the actual lens performance of a lens is by ray tracing where ray obliquity is taken into account. To do so the actual lens eye situation must be simulated. The optimisation procedure of progressive addition lens design provides control of the performance of the lens in selected areas. The invention calculates the best formulas for reducing surface and oblique astigmatism.

Figure AI.43a is contour plot of the surface astigmatism of a progressive lens surface before the computerized optimisation, while AI.43b is the contour plot of the same lens after optimisation. Each contour represents 0, 50 D of surface astigmatism. As it is seen from the drawings the lens after optimisation by computation of 96 points pre-selected presented smaller values of astigmatism, improving in such way its performance.

Dufour, et al (1989) for Essilor proposed a progressive ophthalmic lens, where the wearer can observe through the intermediate vision zone an object such a computer screen for long time periods with out trouble. In such a lens each line on the progressive surface parallel to the main progression meridian substantially satisfies at every point the equation

$$\mathbf{1/R_1 - 1/R_2 = constant}$$

where R_1 and R_2 are the principal radii of the surface at the point concerned. This means that along the progressive area any point on a parallel line to the main meridian for a width of at least 15 mm will present constant astigmatism. This provides a wide progression corridor usable for long continuous work. Also, the main progression meridian is substantially umbilical, meaning that at each point on it the principal radii are substantially equal. Figure AI.44a shows how the surface power is spread on the lens, while AI.44b shows the lines of equal astigmatism with an area 12 showing the parallel lines to the main meridian of constant astigmatism.

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Figure AI.43. *Barkan, et al. method for improving progressive lens designs. a) Is a contour plot of surface astigmatism of a lens surface to be optimised b) is a contour plot of the surface astigmatism of the same lens surface after optimised by Barkan's method. (From Barkan, 1989)*

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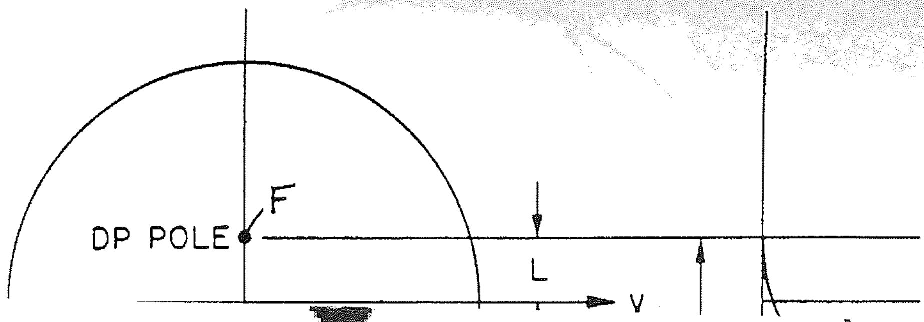
Figure AI.44. *Dufour, et al progressive ophthalmic lens. a) Shows the lens construction, the areas of substantially constant power and the curves of equal power of the progressive surface. b) Shows the curves of equal astigmatism along the lens surface. (From Dufour, 1989)*

Winthorp (1989) provided a different lens design than the ones known so far. In such a design the distance and near vision zones are not in fact zones but two mathematical points. In this way the power of the unwanted surface astigmatism is reduced to a minimum by distributing it over a larger area. So in the distance and near vision zones, which are actually points, each of these points is surrounded by an area of optical stability, having a series of contours of successively different constant mean surface powers around them

The distance and near zone power points comprise the poles of a bipolar system of surface power contours. The contours are selected in such a way as to achieve a smooth and pleasing distribution of surface power and astigmatism. The distance and near power points are connected by an umbilic line of progressive power.

This construction is illustrated schematically in Figure AI.45a where points F and N comprise the poles of a bipolar system of optical power. Figure AI.45b show the contour plots of the lens design. Figures AI.45c, d illustrate the iso-power lines of mean surface power and the iso-astigmatic surface power lines on such a lens design.

a)



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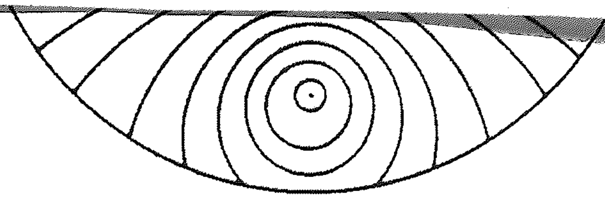
b)



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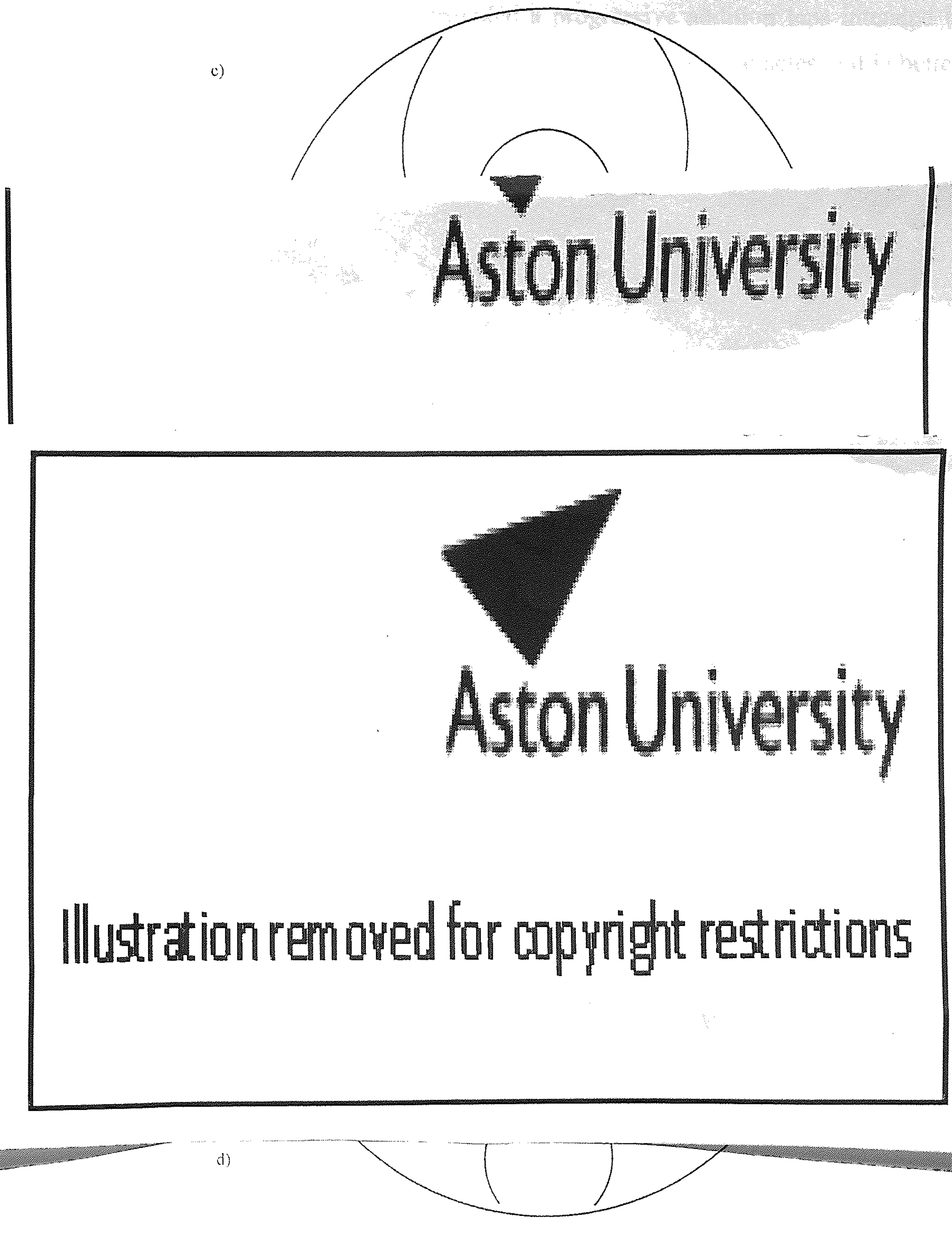


d)

Figure AI.45. *Winthorp's progressive addition lens design. a) Represents the construction of the lens bipolar system with poles F and N being the far and near points. b) Are contour plots representing the geometry of such a lens. c) Are contour plots of constant mean surface power d) are contour plots of constant surface astigmatism. (From Winthorp, 1989)*

Barth (1990), for Rodenstock, provided a progressive addition lens intended to be used only for intermediate and near vision, with half-eye spectacles and is better for emmetropic presbyopes.

The concept was to use a known progressive addition lens only the surface astigmatism that all such designs presented was transposed into the distance vision area by mathematical means so that this irritating aberration is cut off when the lens is mounted on a half-eye frame. The design used could be a symmetrical one relatively to the main meridian presenting in the progression zone lines of constant power horizontally. The progression corridor, which extends from point a point 6 mm above the geometrical centre of the lens to 14 mm below, is free of astigmatism and wide enough to permit clear intermediate vision. The power increased linearly through the corridor.

Figure AI.46 shows an uncut progressive addition lens where BF and BN are the distance and near reference point. Line 2' is the upper rim line of the frame (4) is the intermediate vision zone of the lens and (5) the near.

Figure AI.46. *Front view of an uncut progressive addition lens used for half-eye frames. The rim of the frame is shown by line 2-2'-2. (From Barth, 1990).*

Kitani (1990) for Hoya tried to solve the problem that exists with the convergence of the eyes during near reading. The main meridian of a progressive addition lens according to Kitani should not be a straight line connecting the distance and near vision centres but was displaced toward the nose, while the displacement was varied depending upon the addition of the lens. If the addition is smaller than 1.50 D, the main meridian line lies above the straight line connecting the distance and near vision centres, while if the addition is larger than 2.50, the main meridian line lies below the straight line connecting the distance and near vision centres.

The concept of this invention is based on that there is a great difference in the way that the sight lines shift from distance to near vision between presbyopia persons at the early and late stages. Figure AI.47 shows how the principal meridian line M is disposed. Points 2, 3 are the centres of distance and near vision zones. The distance between points 2, 3 is 16 mm and the meridian M is displaced 2.5 mm towards the nose. Y is the bisector of the principal meridian M, which is parallel to LL'. If the lens presents an addition smaller than 1.50 the principal meridian 4 follows a direction indicated by point c, which is above the intersection 7 of the principal meridian and the bisector Y. If the lens has an addition greater than 2.50 the principal meridian 6 follows a direction indicated by point d, which is below intersection 7. For addition of 1.75 to 2.25 the main meridian follows a direction indicated by points, which are in the vicinity of the point of intersection 7.

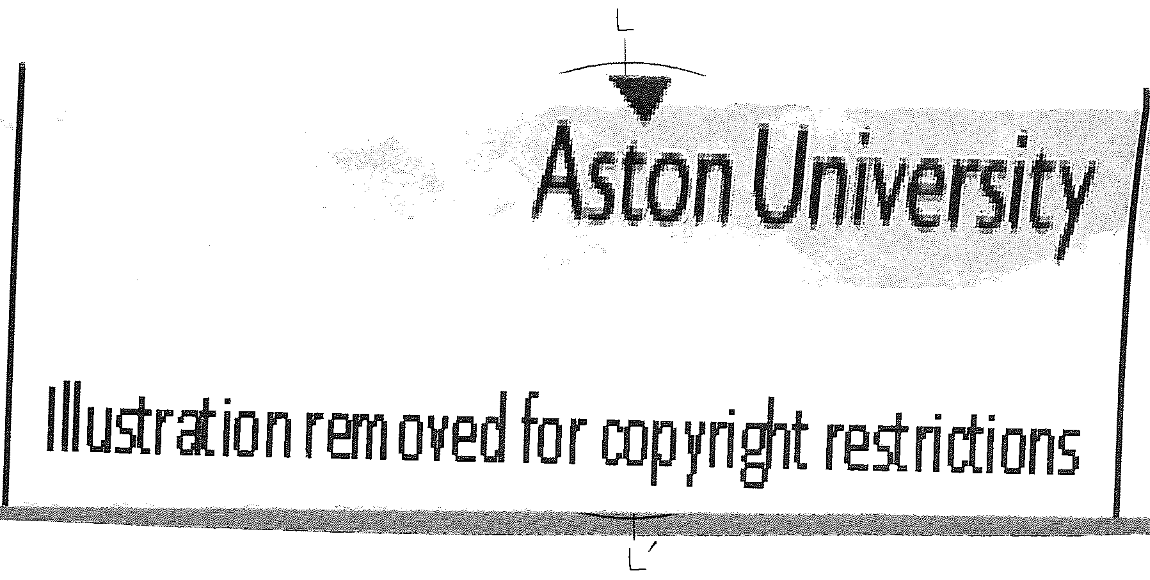


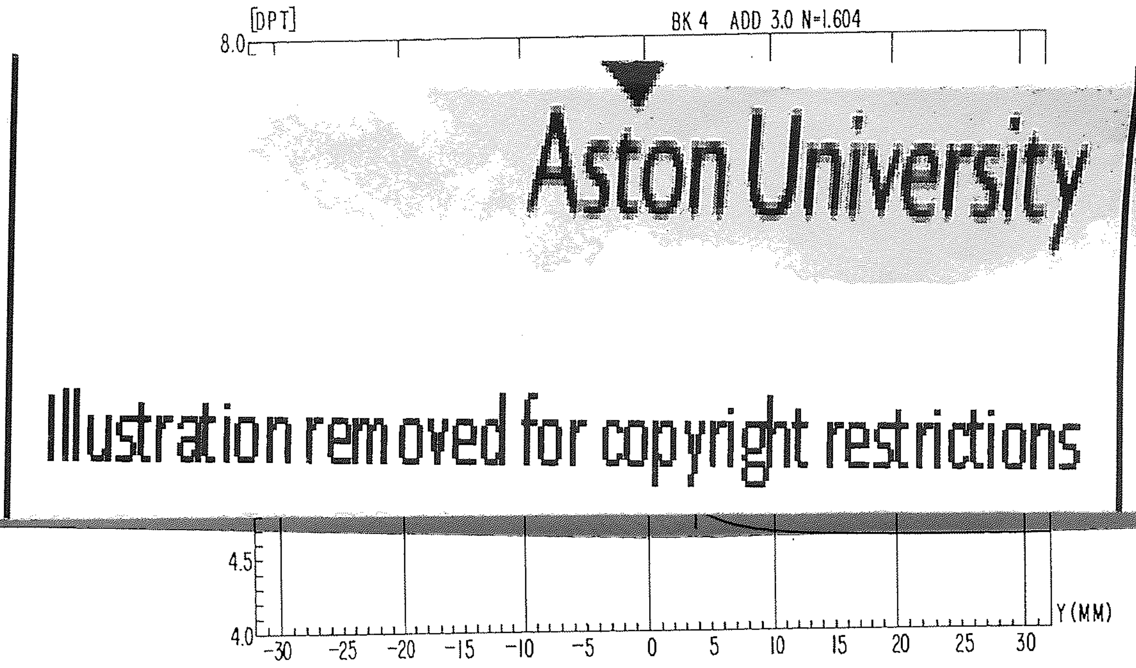
Figure AI.47. *Showing the way the principal meridian is displaced according to the power of the addition. (From Kitani, 1990)*

Guilino, et al. (1990) for Rodenstock provide a progressive addition lens where the lines of the same surface refractive power run mainly horizontally mainly in the main meridian region.

This was achieved by selecting the progressive surface in such a manner that the change in the curvature of the horizontal sections with increasing distance from the main meridian is yielded by superimposing two functions F_1 (x,y,) and F_2 (x,y). The two functions were superimposed so that the absolute values of the amplitudes of both functions change reversely along the main meridian in the progressive zone. Figure AI.48a shows the progressive power law on the main meridian.

The surface astigmatism, in such a design is concentrated in the peripheral regions and in particular in the lower lateral peripheral regions. The described progressive addition lens was intended for normal use, where a comparatively large distant portion free of astigmatism was the main characteristic. The progression corridor started 4 mm above the geometrical centre of the lens and ended 12 mm below.

Figure AI.48b shows the lines of the same refractive power, which increase in value from distance to near vision areas, extend practically in a horizontal direction in the progressive zone area near the main meridian. This produces a pleasant uniform progressive increase when the wearer does not lower his eyes exactly along the main meridian. Figure AI.48c shows the surface astigmatism in the lateral peripheral regions of such a lens.



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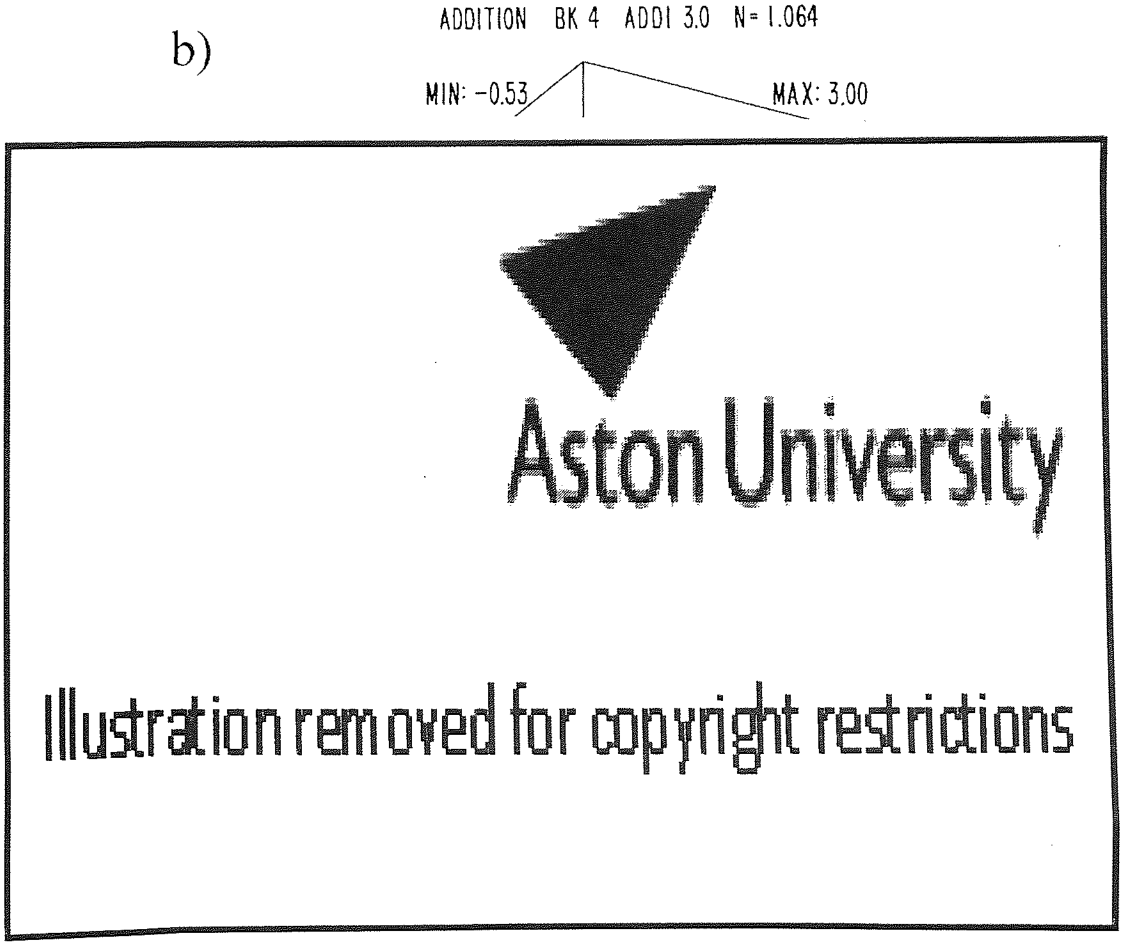
a)

b)



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c)

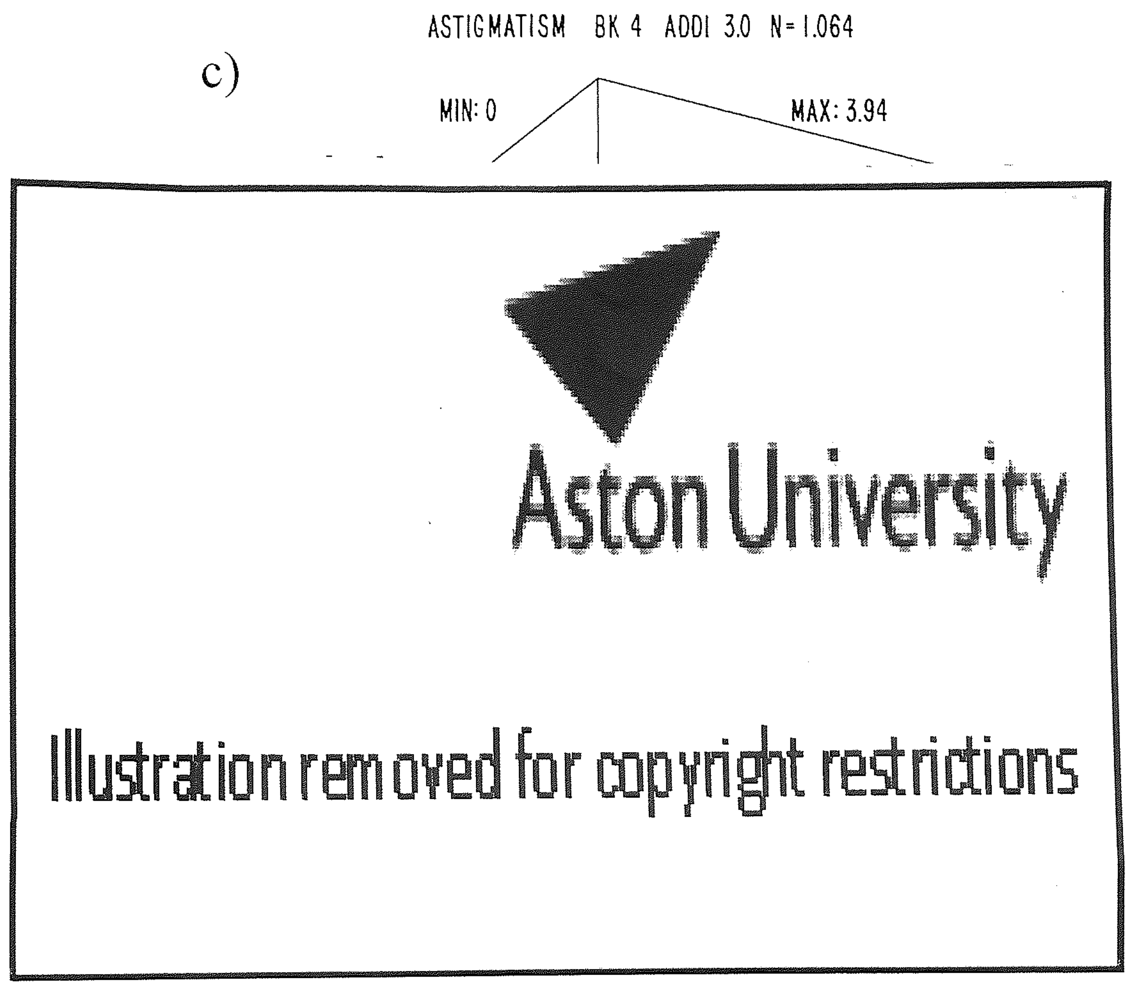

Figure AI.48. *a) Shows the progressive power law of the proposed lens. b) Shows the surface power contour lines. c) Shows the surface astigmatism contour lines. (From Guilino, 1990)*

Takahashi, et al. (1991) for Nikon Corporation proposed a progressive addition lens where a wide clear vision area is assured in the region of distance vision, also visibility is improved in the intermediate portion where aberrational density is reduced to minimize distortion and blurring of an image. The high aberration-concentrated area at each side of the principal meridional curve is moved to the region for near vision, so a user who wears this type of lenses for the first time can comfortably wear them.

Figure AI.49b shows the change of the refractive power along the principal meridian. The curvature ρm and the curvature ρs in a direction perpendicular to the principal meridian have a minimum value near the center OF (distance vision center). Above OF these curvatures increase and actually ρm ≠ ρs. This is made so in order to minimize the astigmatic aberration produced due to the fact that the eye rotates at angles outside the optical center of the lens. Lower than OF the two curvatures increased downward in the intermediate portion P reaching a maximum value at an upper position in the near portion N, and then decreased toward the periphery of the near portion N. A condition ρm = ρs occurs lower from OF to almost the center of the intermediate portion P. Below the center of progression again the two curvature are ρm ≠ ρs.

The increase ΔD (diopter) of the average surface power above the center of distance vision OF with respect to the additional power A is given by the condition

$$0,02A \leq \Delta D \leq 0,2A$$

The gradient Dk (diopter/mm) for such an increase is given by the following condition

$$0,002A \leq Dk \leq 0,02A$$

The increase ΔD (diopter) of the surface power from the center of distance vision OF to the eye point position E is given by the condition

$$0,03A \leq \Delta D \leq 0,15A$$

having a gradient Dk (diopter/mm) that satisfy the following condition.

$$0,003A \leq Dk \leq 0,025A$$

Figure AI.49a shows the iso-astigmatic lines of such a lens design with A=2.50 D. As it is seen the astigmatism in the distance vision area is limited due to the increase mentioned above of the average refractive power while at the near vision area the decrease of the average refractive power reduced the astigmatic density presented lateral to the near vision area.

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Figure AI.49. *Takahashi, et al. progressive addition lens. a) Is a graph showing the iso-astigmatic lines of such a design with Add=2.50 D and each line represent 0.50 D. b) is a diagram showing the progressive power law along the principal meridian. (From Takahashi, 1991)*

In *1991, Takahashi, et al.* for Nikon Corporation again give more mathematical details of the lens design previously described.

Guilino, et al. (1991) on behalf of Optische Werke G. Rodenstock, had a different approach. The progressive addition ophthalmic lens they proposed comprised of an intermediate area where a varying refractive index n of the lens material existed along the main line of vision. This main line of vision, which is the same as the main principal meridian in usual progressive lenses, could follow the convergence of the eyes when lowering the glance for near vision.

The refractive index n was a function f(y). The radii of curvature along the main vision line were selected in such a manner that the saggital power S'_{sag} and the meridional power S'_{mer} were the same.

The refractive index functions contributing to the increase in refractive power and to the correction of astigmatism were:

$$\mathbf{n(x,y)=n(y)+2n_2\ (y)*x.^2\ /(1\ +(1\ -\ x(y)+1)\ *4n_2^2\ (y)*x^2))^{1/2}}$$

and

$$\mathbf{n(x,y')=n(y')+2n_2\ (y')\ *x^2\ /(1+(1-\ x(y')+1)\ *4n_2^2\ (y')\ *x^2))^{1/2}}$$

As it can be seen from the drawing of Fig. AI.50a the (Δn) difference in the refractive index obtained was Δn = 0, 09. In this patent is not given any information on how this gradient of the refractive index could be attained and how the steps of the refractive index gradient could be controlled. It is more a mathematical model on how a gradient of refractive index in the intermediate area could be used to produce an addition in refractive power and reduce the astigmatism presented on the main line of vision.

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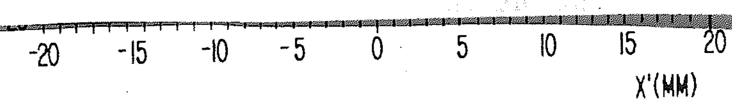

b)

Figure AI.50. *Guilino, et al. progressive ophthalmic lens. a) Illustrates the change of the refractive index along the lens. b) Shows the astigmatism produced with such a lens (From Guilino, 1991)*

Ueno, et al. (1991) for Nikon introduced a progressive power lens. Such a progressive power lens, even when the intermediate vision zone is shortened, provided a wide field of view in the lower portion of the distance vision zone, while in the intermediate and near vision zones distortion and fluctuation of an image is eliminated as much as possible. Such a characteristic makes side view of a wearer to be comfortable, and is well balanced in terms of aberrations. A lens design such as this can be worn from someone, who wears lenses of this type for the first time, without feeling uneasy.

In order to achieve the above disadvantages the progressive lens design had a principal meridian curve as the one showed in Figure AI.51a The vertical and horizontal sectional shape of such a lens design in the distance vision zone is formed so that the values of the vertical and horizontal radii of curvature are increased compared to the radii values of the principal meridian as it goes away from the principal meridian along a horizontal section in an upper portion of the distance zone, then the values are kept constant near a central portion of the distance zone and then are decreased in a lower portion of the distance zone and in an upper region of the intermediate zone. In a lower region of the intermediate zone the values are increased and then in the lower region of the near zone are decreased. Figures AI.51b,c show the values of the vertical and horizontal radius of curvature in horizontal sections away from the principal meridian, which is expressed as (Vy) in the two diagrams. The horizontal and vertical sections outside the principal meridian are expressed in degrees. Figure AI.51d shows the iso-astigmatic lines of such a surface design. As it is seen by controlling the horizontal and vertical radii of curvature sideways of the principal meridian the astigmatism is minimum in the distance vision area and is kept low in the intermediate and near zones.

a)

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b)

d)

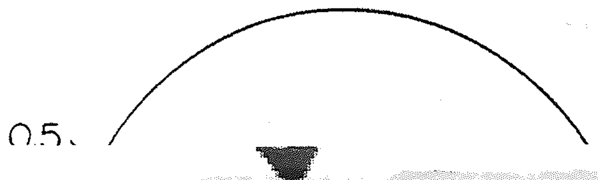

Figure AI.51. *Ueno, et al. progressive power lens. a) Is a graph showing the progressive power law related to the principal meridian. b) Is a graph showing the change of the vertical radius curvature along horizontal sections at positions away from the principal meridian and with reference to the vertical radius value at the principal meridian. c) Is a graph showing the change of the horizontal radius curvature along horizontal sections at positions away from the principal meridian and with reference to the horizontal radius value at the principal meridian. d) Is a graph showing the astigmatism presented by the lens surface. (From Ueno, 1991)*

Winthrop (1992) for American Optical Corporation continuing his work in *US 4861153* provided a series of ophthalmic progressive power lens for general purpose, occupational and dynamic activities. Depending on the type of intended use the meridional power law is selected so the lens is:

a) *For general use*

The lens is characterized by an 8^{th} order polynomial power law and is selected so to provide adequate focal stability for the distant and near visual fields.

b) *For occupational use*

A 4th order polynomial power law characterizes the lens. Specifically for a design for occupational use the meridional power law is selected to provide a relatively large and stable near vision zone and a relatively small distance portion. The maximum astigmatism of the lens is located above the 0°-180° line of the lens and is even less than that of the general-purpose lens: 1, 10 D vs. 1.51 D in a 2.00 add lens. This lens works particularly well in a computer work environment.

c) *For dynamic use*

An 8th order polynomial power law characterizes the lens. The meridional power law provides a large, stable distance-viewing area and a relative small reading area. This type of lens is used in those visual situations in which far and far-intermediate distances predominate, and where freedom from distortion is required, so this lens suits for example a professional driver or a person involved with sports.

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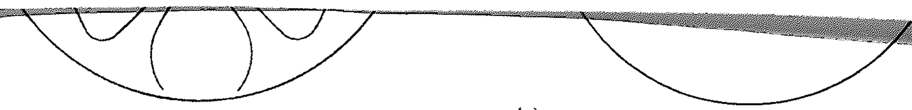

a) b)

c)

Figure AI.52. *a) Is a schematic diagram of the surface astigmatism and the mean refractive power of a lens for general use b) is a schematic diagram of the surface astigmatism and the mean refractive power of a lens for occupational use. c) Is a schematic diagram of the surface astigmatism and the mean refractive power of a lens for dynamic activities (From Winthorp, 1992)*

Kelch, et al. (1993) for Carl-Zeiss continued the work done in US 4,606,622. (This design was launched in the market under the trade name "GRADAL HS"). The new lens design had a multifocal surface, which was twice continuously differentiable. The mean surface refractive power ranged between +3.0 D to +7.0 D in the distance zone, and the addition ranged between +0.75 D to +3.0 D. This lens design had a non-umbilical principal meridional line, which was curved toward the nose and partitioning the multifocal surface into a nasal region and a temporal region.

The two reference points for near B_N and for far B_F, had a distance of 21 mm while BN was also inwards 2 to 3.5 mm depending on the addition. 75% of the addition was reached along a distance of at most 10 mm on the principal meridional line in the progression zone. In the progression zone, the width was at least 5/Add mm for a surface astigmatism < 0.5 D. At the near-reference point B_N, the width of the near-vision zone is at least 7+9/Add mm for a surface astigmatism <0.5 D. In the far-vision region, the surface astigmatism is <0.5 D for all points where φ > 45-30/Add where angle φ is measured with reference to a horizontal line passing at a point which is 4 mm perpendicularly below the far-reference point B_F.

Examples of the lens design were given for additions 1, 00 – 2, 00 – 3, 00 D. For these additions the 75% of the surface power change, starting from a point G, which is 7 mm below the far-reference point B_F, was reached at about 9 mm in the progression zone with the length of the progression zone being 14 mm.

For addition 1.00 D the minimal width of the progression zone was more than 5 mm, while the width of the near-vision zone was about 16 mm close to the near-reference point B_N. The surface astigmatism for all points having φ >15° lies below 0.5 D. For addition 2.00 D the minimal width of the progression zone was more than 2, 5 mm, while the width of the near-vision zone was about 12 mm close to the near-reference point B_N. The surface astigmatism for all points having φ >30° lies below 0.5 D. For addition 3.00 D the minimal width of the progression zone was more than 2 mm, while the width of the near-vision zone was about 10 mm close to the near-reference point B_N. The surface astigmatism for all points having φ >35° lies below 0.5 D. Figures 2.4.8a,b,c show the surface astigmatism and the mean surface refractive power of lenses having 1,00-2,00-3,00 addition power.

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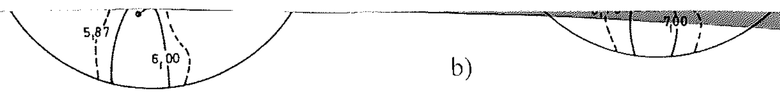
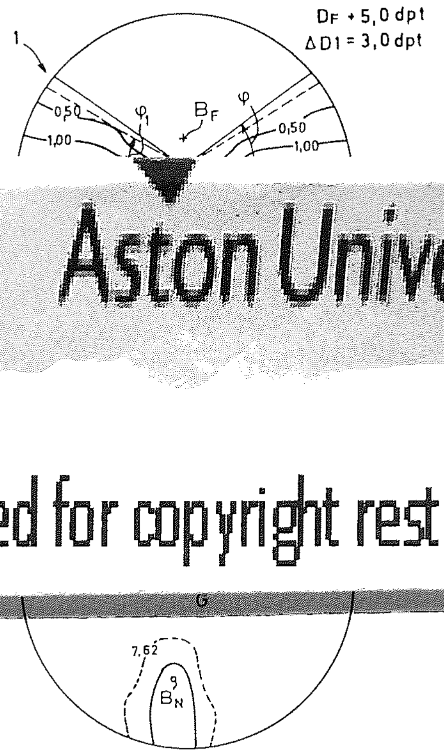


a) b)



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c)

Figure AI.53. *Kelch et al multifocal lens. a) Is a schematic diagram of the surface astigmatism and the mean refractive power of a lens with Add=1.00 b) is a schematic diagram of the surface astigmatism and the mean refractive power of a lens with Add=2.00 c) is a schematic diagram of the surface astigmatism and the mean refractive power of a lens with Add=3.00 (From Kelch 1993)*

Barth, et al. (1993), for Optische Werke G. Rodenstock, produced a progressive ophthalmic lens having positive distance portion power. The lens had a vertical prism for reducing the thickness of the lens, having a size ranging from approx. 0.25 cm/m to approx. 3.00 cm/m, which has a subjacent base so that the optical axis is moved in the direction of the near portion (NT). With such a prism introduced the peripheral thickness of the lens is levelled regarding the area of the distance and near vision zones.

The surface astigmatism presented in the distance and near vision zones is utilized for the compensation of the oblique light bundle astigmatism. More precisely, the tangential radius of curvature R_{HM} (in direction of the main meridian) of the progressive surface along the main meridian (HM) is increased linearly going away of the distance reference point while the sagittal radius of curvature R_{sag} (perpendicular to the main meridian) of the progressive surface is practically constant for all the points on the main meridian in the distance vision area. In the near vision area, the sagittal radius R_{sag} of curvature is not constant and it becomes smaller almost linearly as a function of the distance from the near vision reference point. The radius of curvature R_{HM} in the direction of the main meridian is either practically constant or increases on the main meridian in the near vision zone. The equations for the above relations are:

$$\mathbf{R_{HM}\,(y_{BN} - 15 < y < (y_{BN}) \geq R_{HM}\,(y = y_{BN})}$$
$$\mathbf{R_{sag}\,(y < y_{BN}) < R_{sag}\,(y = y_{BN}) < R_{HM}\,(y = y_{BN})}$$
$$\mathbf{|\,dR_{sag}/d1\,| \approx const > 0 \text{ for } y < y_{BN}}$$

with $|\,dR_{sag}/d1\,|$ being the variation of the curvature perpendicular to the main meridian in points on the main meridian and y_{BN} being the y-coordinates of the near vision reference point.

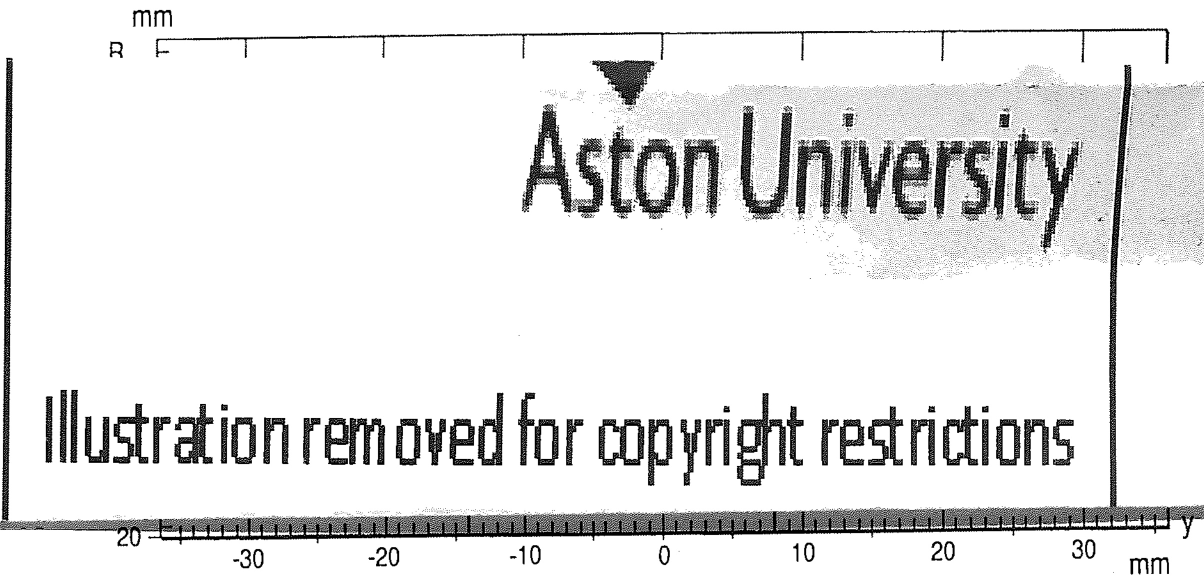

Figure AI.54. *Barth, et al. progressive ophthalmic lens with positive distance power. Diagram showing the variation of the sagittal and the tangential radii of curvature along the main meridian. (From Barth, 1993)*

Pedrono (1993) for Essilor International introduced a multifocal ophthalmic lens. The provided multifocal ophthalmic lens, or more precisely a family of lenses, takes into account the up and down position of the eyes in the ocular orbit and the posture of the wearer's head. This position depends on the viewing distance and on the inclination of the head in the sagittal plane (the vertical plane passing through the middle of the line segment joining the centres of rotation of the two eyes, and perpendicular thereto). Also it takes into consideration the pantoscopic angle, which is normally around 12°, the changes (reduction) in the near viewing distance with increasing age of the wearer and the ametropia of the wearer for distance vision.

In order to provide a better progressive addition lens regarding the above the principal meridian situated in the intermediate and near zones is divided into two segments. The first segment DC is inclined at an angle α to the vertical where the value of α is an increasing function of the power addition A of the lens,

$$\alpha = f(A) = 1{,}574A^2 - 3{,}097A + 12{,}293$$

and the second segment CM', which is inclined at an angle ω to the vertical where ω is smaller than α.

$$\omega = g(A) = 0.266A^2 - 0.473A + 2.967$$

At the point C where the two segments meet, the mean sphere value of the surface corresponds to a power addition lying in the range 0.8 to 0.92 times the nominal power addition of the lens. Figure AI.55a shows such a progressive lens design. Point 0 is the geometrical centre of the lens, L is the point where the distance vision power is measured, P is the point where the near vision power is measured, and D is the point where the lens is mounted on a frame at the pupil centre. L is 8 mm, D is 4 mm and P is –14 mm distance from point 0. Depending on the Addition value angles α and ω vary. (Figure AI.55b). Figure AI.55c shows how the value of the mean sphere of the progressive surface, change along the principal meridian with respect of the addition.

In such design also as mentioned before due to the ametropia of the wearer for distance vision a prismatic effect is induced. Taking into consideration the above an angle α' had to be added at angle α in order to compensate and minimize the horizontal component of the prism induced, especially with hypermetropia and high additions. Figure AI.55d shows the angle α' to be added relatively to the proscription of the wearer for distance vision.

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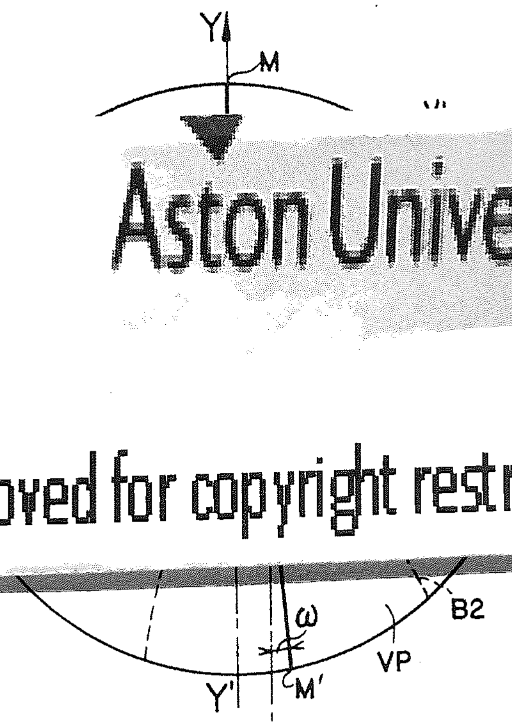

a)

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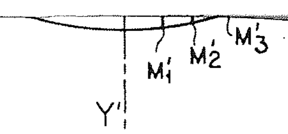
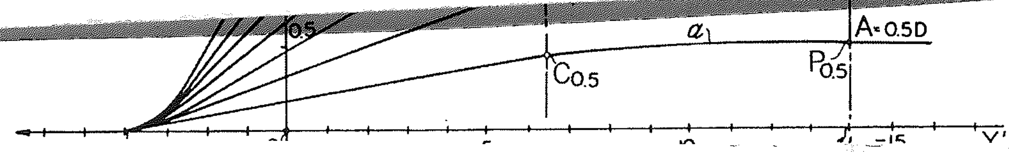


b)



d)

Figure AI.55. *Pedrono's progressive multifocal ophthalmic lens. a) Is a front view showing the aspherical surface of the lens with the two segments of the principal meridian in the intermediate zone. b) It shows the shape of the main meridian of the aspherical surface for three different values of power addition. c) Show the variation of the value of the mean sphere of the progressive surface relatively to the Addition. d) Angle α'relatively the prescription for far. (From Pedrono, 1993)*

Waido (1994) for Gentex Optics, Inc. proposed a lens having near vision and far vision poles and a progressive surface between these poles. It was a same philosophy design with the one proposed by Winthrop in *U.S. Pat. Nos. 4,861,153 and 5,123,725*. Such lens design for progressive lenses is constructed in accordance with the bipolar principle. As is explained in these patents, in such a lens both the near vision zone and the distance vision zone were reduced to mathematical points or poles.

According to Waido the progressive surface had two regions adjacent to the poles and a middle region between the poles. The power law provided power gradients in these regions adjacent to the poles, which are relatively steep as contrasted with relatively gradual power gradients in the middle region thereof between the poles. The lens differs from Winthorp's design in that it had a vertical principle meridian, in which the power law had the formula

$$P=7-Y/19+0.104e^{1.44}(Y/19)^2 \sin(\pi Y/19)$$

where P is optical power in dioptres and Y is a Cartesian coordinate whose axis is the vertical principal meridian of the lens. The maximum surface astigmatism was about 0.44 D., while the average surface astigmatism of about 0.21 D.

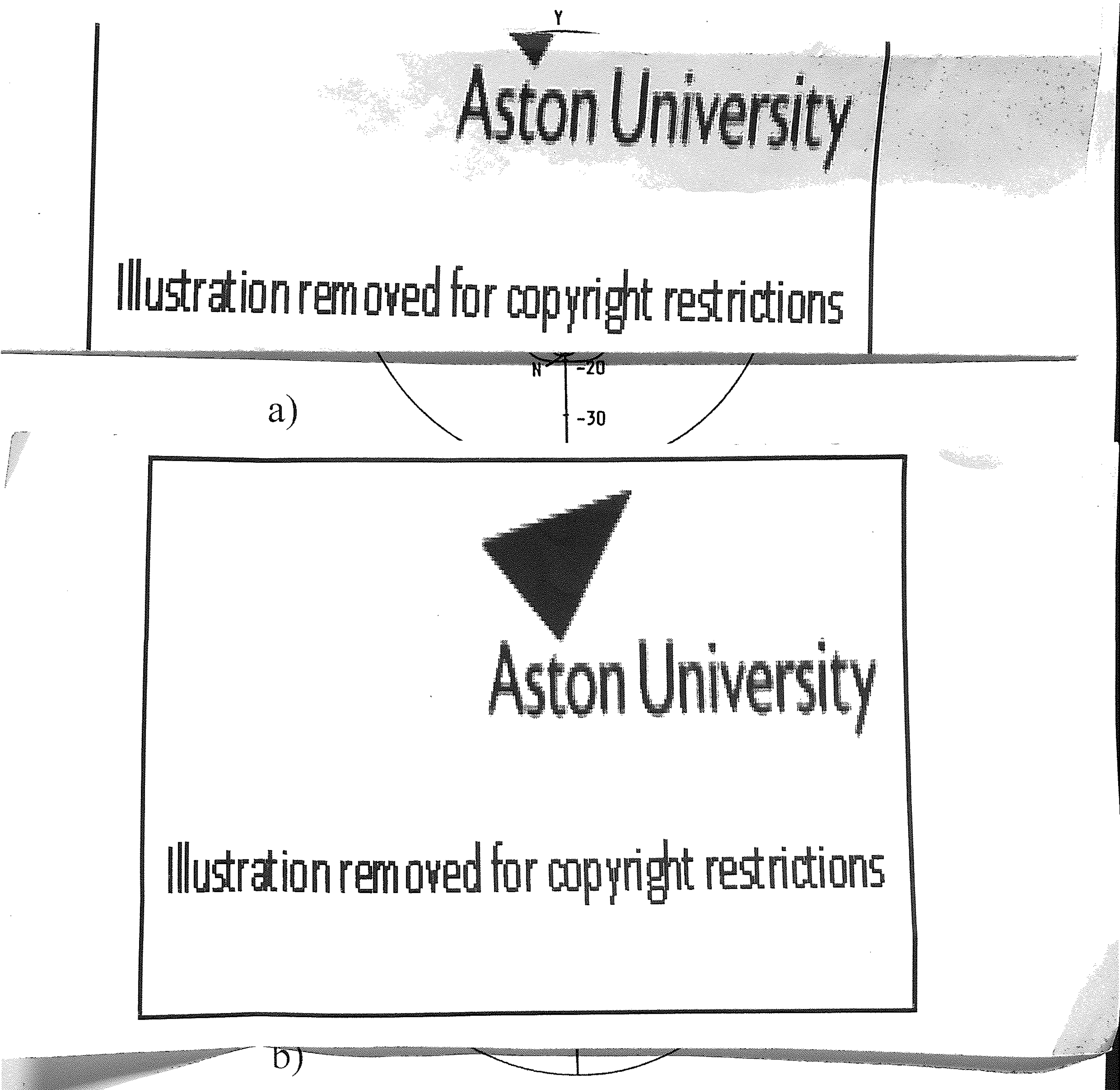


Figure AI.56. *Waido's progressive lens for occupational use.a) Schematic diagram showing the mean add in 0.25 dioptre contour intervals of the surface of a progressive addition lens designed on the bipolar principle b) It is a schematic diagram of the astigmatism in 0.25 dioptre contour intervals of the surface (From Waido,1994)*

Kelch, et al. (1995) for Carl-Zeiss, produced a spectacle lens, which was suitable for individual use situations. This means that the lens was design according to the individual wearer requirements.

The progressive surface of the produced lens is the same according to the *US. Pat. 4,606,622*. The one surface that is different is the back surface, which is used as the prescription surface. This was an aspherical surface without point and axis symmetry, which acted as to provide the dioptric power at the reference points for far and near vision and to eliminate increases of imaging errors.

For determining such a prescription surface, the basis of the computation takes into account the corneal vertex distance, the distances to the object viewed, the forward inclination of the spectacles frame (pantoscopic tilt), the shape of the frame and the depth of curvature.

Especially if the shape of the frame and cantering are known, then the required prismatic actions can be distributed to the right and left lens in order to provide the best thickness and weight of such lenses. Also for a known shape of the spectacles frame, an optimal distribution of the aberrations can be obtained with the aberrations being shifted into the portions, which will be cut away. In cases where unusual depth of curvature was present according to the prescription of the wearer, like in case of anisometropia the lenses could be optimised in appearance and in the aniseikonia produced.

These lenses are characterized in that the imaging quality is maintained even for extreme deviations of the actual use situations from the average use situations (that is, minimum imaging errors occur) without the necessity of providing an individual multifocal surface for each individual user. The corrections to the prescription surface, which are necessary for this purpose, can be realized with numerically controlled machines.

Kato (1995) on behalf of Sieko Epson Corporation proposed a progressive power lens, in which the weight and thickness was reduced, and provided an excellent field of view by improving aberrations.

In one of the embodiments of such a lens design the curvature of the distance portion (1) had a constant value at an interval of at least 12 mm from the vicinity of the centre to the peripheral portion of the distance portion, and then changed, reduced or increased depending on whether the distance prescription corrects hypermetropia or myopia, while the curvature of the reading portion (2) had a constant value at an interval of at least 7 mm from the vicinity of the centre to the peripheral portion of the reading portion, and then was changed. The lens was made of a plastic material having a refractive index of not smaller than 1.55.

Such a progressive power lens, which had a prescription for correcting myopia in the distance portion region, was characterized in that a prism, having a magnitude Pt, was provided with a base in the direction of 90°, for reducing thickness, weight and aberrations. The power of the prism Pt satisfied the following relationship:

$$-\frac{(4.0 - ADD)}{9} \times PW \leq Pt \leq \frac{(8.0 - ADD)}{9} \times PW$$

where PW is the prescription for myopia correction and ADD is the addition power.

An example of such design is shown in Figure AI.57. The distance portion (1) had a refractive power of +3.00 D and an Addition power +2.00 D. The refractive index of the lens was n=1.60. A cross-section of the lens distance portion 1 taken along the principal gazing line is shown in Figure AI.57b, in which (8) indicates the surface on the object side of the lens, and (9) the surface on the eye side. (8') and (9') indicated by the broken lines are the surfaces of a conventional progressive power lens. Although the conventional surface (8') has a constant curvature, the new surface (8) was reduces in curvature from the vicinity of the centre towards the peripheral portion of the lens.

Figure AI.57c shows the astigmatism presented by such a progressive power lens. As compared with a conventional lens, in the distance portion (1) astigmatism is reduced in the upper peripheral portion, giving a widen field of view. Moreover, the thickness of the lens is reduced.

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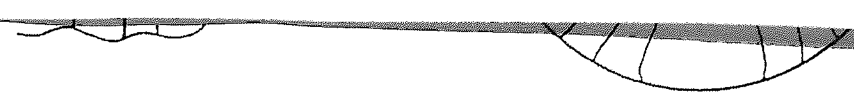


b) c)

Figure AI.57. *Kato's progressive power lens. a) Is a front view of the progressive lens b) is a cross-sectional view of the distance portion of such a lens. b) Is a view of the astigmatism presented by the lens (From Kato, 1995)*

Harsigny, et al (1996) on behalf of Essilor produced a progressive multifocal ophthalmic lens in which visual comfort is at a maximum in the distance and near vision regions in which the variation in mean sphere is very small. In the lateral portions of the intermediate vision region, the isosphere lines are close together but substantially horizontal, and peripheral vision remains comfortable. Ease of dynamic vision is preserved, for near and distance.

According to the invention the mean sphere gradient in the intermediate vision region is a linear function of the power addition value, while the effective progression length of the principal meridian is about 15 mm. The ratio of the maximum value of the mean sphere gradient to the power addition was less than a coefficient K_s max (For add < 1, K_s max = 0.07 mm^{-1}, 1< add < 2, K_s max = 0.08 mm^{-1}, 2 < add, K_s max = 0.09 mm^{-1}

On the other hand the ratio of the gradient of the cylinder of the surface to the power addition value had a value less than a coefficient K_c max equal to 0.165 mm^{-1}. The maximum value of the gradient was located in regions laterally of the principal meridian of progression in the intermediate vision where a 0.5 diopter isosphere line of the surface made an angle of less than 30° with the horizontal axis of the lens in the distance vision zone.

In accordance with the invention, progressive multifocal lens wearer comfort is increased if limitation to cylinder variations at the lens surface is applied. For each lens having a power addition value A, the maximum cylinder gradient P_{MC} is equal to:

$$P_{MC} = K_c \max \times A$$

in which:

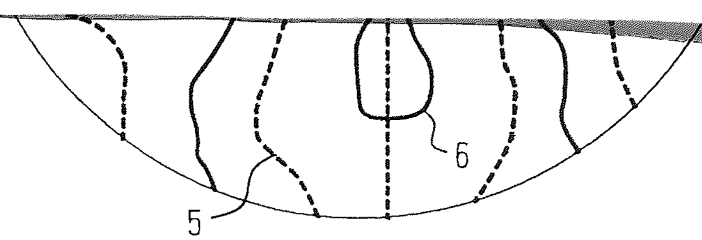
- A is the power addition value,
- K_c max is a constant coefficient, equal to 0.165 mm^{-1}.

According to the above the cylinder gradient exhibits zones of small variation at the distance vision region and the near vision region. The lens thus ensured comfortable vision not only along the principal meridian of progression but also in lateral regions, providing good dynamic and peripheral vision.

Besides a very wide distance vision field and a wide near vision zone was provided. The table AI.2 below gives the width of the near vision field measured horizontally at both sides of a point P -14 mm below the geometrical center O of the lens along the y-axis where the diopter isocylinder line is up to 0.50 D.

TABLE AI.2.

A field width VP	**at point P in mm**
1	**15**
1.5	**12**
2.0	**11**
2.5	**9**



a)

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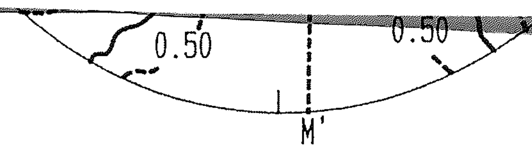

Figure AI.58. *Harsigny, et al progressive multifocal ophthalmic lens. a) Is a front view of the lens showing the principal meridian of progression and lines of mean power level for addition 2.00D b) is a front view of the lens showing the cylinder level (iso-astigmatism) lines for addition 2.00D. (After Harsigny, 1996).*

Umeda, et al (1996) for Nikon Corporation produced a progressive multifocal lens having wider and stable distinct vision areas of intermediate and near vision portions and reducing the maximum astigmatic aberration while securing a sufficiently wide distinct vision area for distance.

In order to achieve the above, the lens is made having a horizontal sectional shape at the lower portion of the distance vision portion, which was a non-circular arc in which the curvature was increased and then decreased away from an intersecting point with the principal meridional curve along a horizontal crossing curve. The horizontal sectional shape at the upper portion of the near vision portion was a non-circular arc in which the curvature is decreased and then made approximately constant away from an intersecting point with the meridional curve. The horizontal sectional shape at the center of the intermediate portion was a non-circular arc in which the horizontal section curvature is decreased away from an intersecting point with the principal meridional curve along a horizontal crossing curve. Figure AI.59a shows the change of the horizontal shape of the lens away from the principal meridian at the different vision zones.

It was actually an asymmetrical progressive multifocal lens wherein the front surface was divided asymmetrically by the principal meridian into a nasal side portion and a temporal side portion. The gradient of the decrease of the horizontal section curvature was larger in the nasal portion from the intermediate portion to the near vision portion than in the temporal portion. With such a lens it was obtainable a sufficiently wider distinct vision area around the eye point E at the distance vision portion F, and the connection between the intermediate portion P and the distance vision portion F was performed smoothly.

Further, as the rate of the decrease of the horizontal section curvature is kept approximately constant from the upper portion to the lower portion of the near vision portion N, it is possible to reduce a maximum astigmatic aberration and the gradient of the astigmatism is made gentle. As a result, while securing a wider distinct vision area as visual performance, the distortion and fluctuation of an image in the side regions can be preferably eliminated, making it possible to eliminate uncomfortable feeling at the time of use as spectacles. Figure AI.59b shows the contours of astigmatism for such a design compared with a conventional one Figure AI.59c.

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6.0

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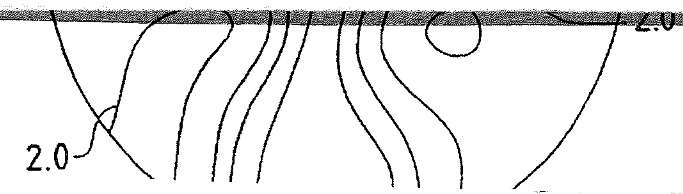
a)



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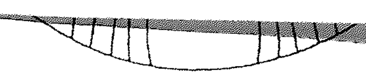


c)

Figure AI.59. *Umeda, et al progressive multifocal lens. a) Is a plan view showing the change of curvatures along the respective horizontal cross sections. Axis Vy and Vz are divided into horizontal sections by degrees deviation from the geometrical center of the lens. b) Is a graph showing the astigmatic aberration on the lens surface c) is a graph showing the astigmatic aberration on the lens surface of a conventional progressive lens for comparison reasons (From Umeda, 1996)*

Smith (1997) for Teijin Chemicals Ltd, produced a progressive addition ophthalmic lens providing a continuous visual field, wherein the mean focal power is defined by a polynomial equation of the eighth order having a form

$$P=b_1+b_2X+b_3X^2+\ldots b_9X^8$$

where b_1 through b_9 are non-zero coefficients and X is the ordinate value of the coordinate axis and wherein the progressive power surface provides a smooth continuous transition of the mean power within the visual field along a line of lateral gaze and a line of ocular convergence.

The progression corridor is umbilicus and asymmetrically bisects the progressive zone following the path of the eye during convergence. This mathematical method used was similar in concept to an ordinary least squares fit in linear regression theory. In such a method 11 points are specified as power requirements along a horizontal cross-section 20 mm down into the progressive zone.

Kitani (1998) on behalf of Hoya Corporation produced a progressive power multifocal lens having a substantially good broad field of view for the eyeglass wearer without increasing time and cost required to produce the prescribed surface

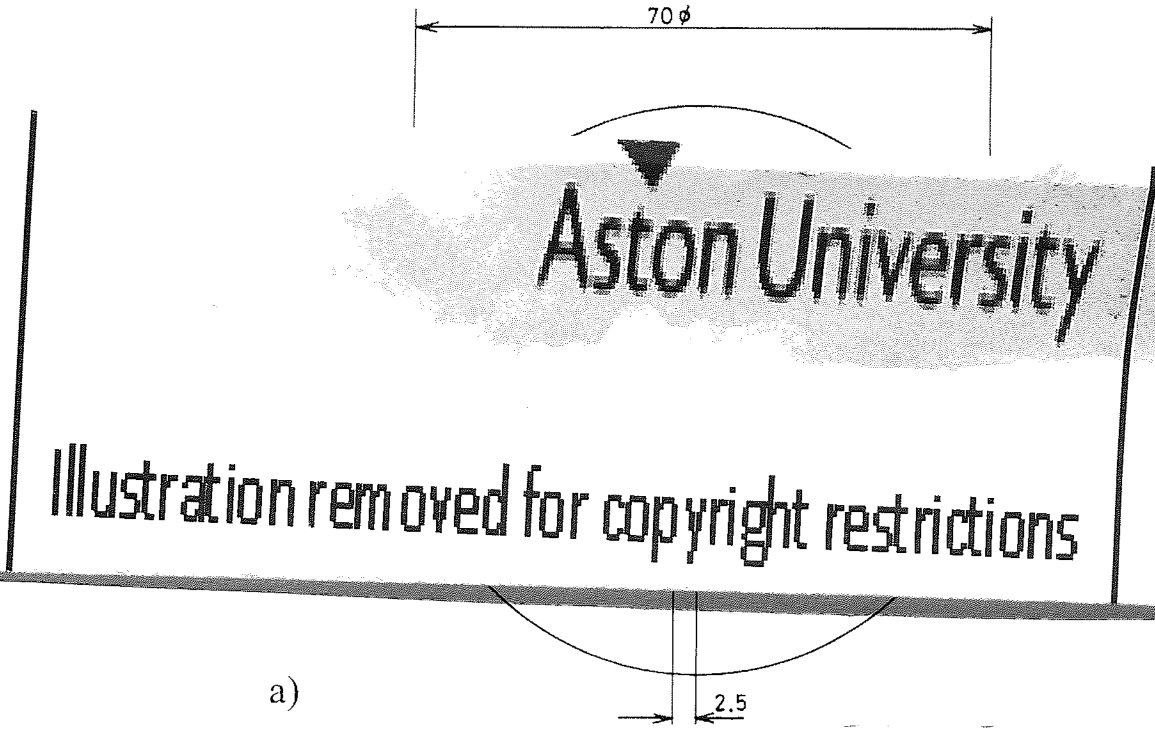
The conventional progressive power lenses so far had been evaluated by representing the performance of the lens surface in the form of a distribution chart or diagram. The distribution charts were examined whether the lens design was suitable for an eyeglass wearer. However, the light actually reaching the eye of wearer is characterized as "transmitted light" meaning that it has been transmitted and refracted by the spectacle lens. For this reason, even though the diagram charts illustrating the optical information distribution on the surface of a lens may be the best, this does not make the lens design superior according to Kitani if the diagram chart for illustrating the optical information distribution in the case of using light transmitted by the lens is not good.

According to the above, what matters in a lens design are not the "surface average refractive power distribution" and the "surface astigmatism distribution" but the *"transmission average refractive power distribution"* and the *"transmission astigmatism distribution"* Consequently, in accordance with Kitani's idea, the optical information distributions in the case of using "transmitted light" are drawn by obtaining all the data necessary by calculation.

The parameters necessary for this calculation are all factors respectively determining the shape of spectacle lenses and the positional relation between each of the eyes of a wearer and an object viewed and the refractive index of the material of the lens.

Figure AI.60a shows a front view of such a lens design for a left lens with 70 mm diameter. The lens is of the laterally asymmetric type with different design for left and right lens. As shown in this figure, in an example given for this lens, the far vision power measuring position F is located 8 mm upwardly away from the geometric centre G. Further, the near vision power measuring position N is at a distance of 16 mm from centre G and also is deviated laterally towards the nose of the wearer by a distance of 2.5 mm. Point E, which is the fitting point when the wearer has his eyes in a front viewing condition, is placed 2 mm upwardly away from the geometric centre G.

Figures AI.60b, c show the distribution of astigmatism firstly for the surface astigmatism plotted conventionally and secondly the transmitted astigmatism. According to Kitani the lens design must be selected so that the transmitted surface astigmatism is reduced.


70 ϕ
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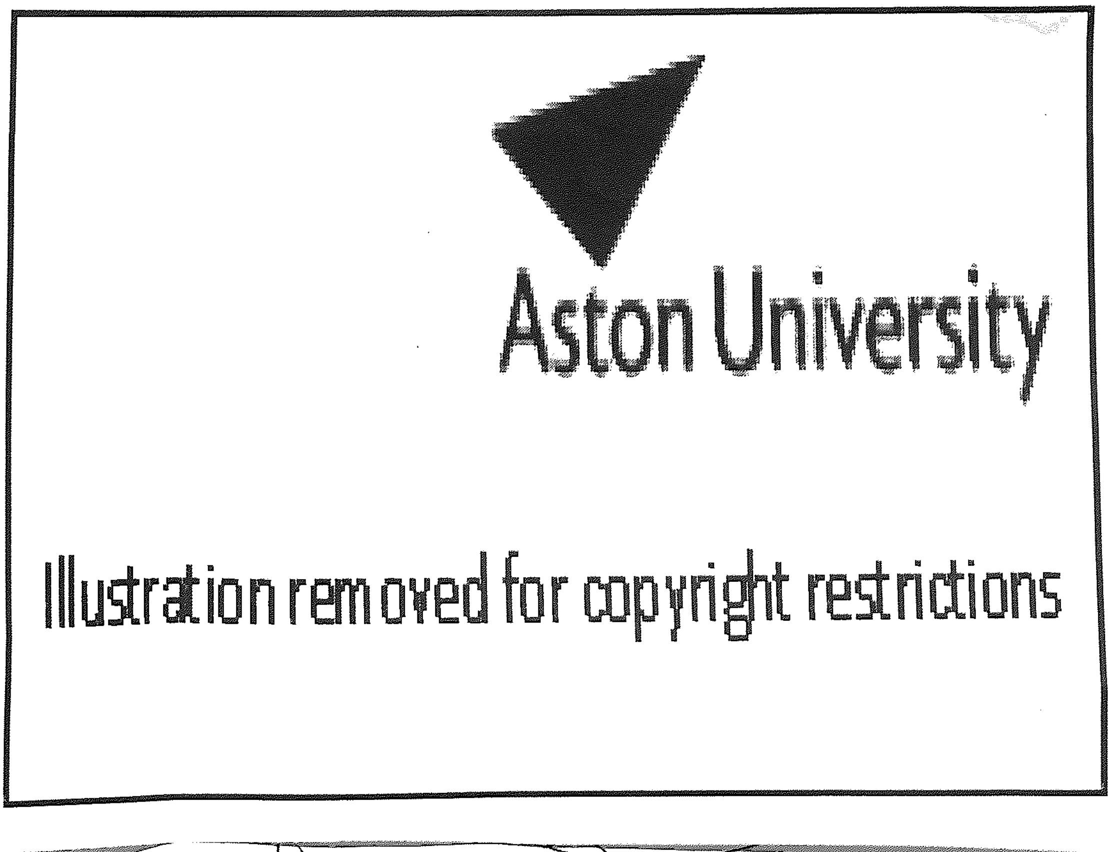
2.5

a)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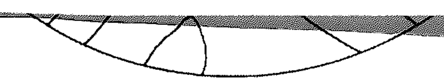


c)

Figure AI.60. *Kitani's progressive power multifocal lens. a) Is a front view of a progressive power lens (which is 70 mm in diameter) for the left. b) Is a diagram for illustrating the surface astigmatism distribution c) is a diagram for illustrating the transmitted astigmatism distribution. (From Kitani, 1998)*

Ahsbahs, et al. (1998) for Essilor introduced another progressive ophthalmic lens. It is well known that the width of the near vision portion and the intermediate vision portion are inversely proportional to the power addition value. Due to this fact, it is difficult for wearers of progressive lenses specially, those with high adds to read a text without the need of head movement in order to maintain good visual acuity.

The design proposed provided the wearer a substantially constant viewing field in the near vision portion regardless of the wearer's ametropy and the lens's power addition. The lens design also provided enhanced reading comfort by allowing the wearer to maintain a natural posture for close reading work

In order to accomplish the above the width of the near vision zone varied not only as a function of power addition A, but also as a function of base curvature B used. The lens thus ensured, regardless of the extent of ametropy of the wearer and of the power addition of the lens, the provision of a substantially constant field of view in the near vision zone of the lens.

According to one example given of the lens, the width of the near vision zone was set at a given height (point P) on the lens between two isocylinder lines having a cylinder value equal to A/2. Depending now of the base curve used or the addition power of the lens this width was made an increasing function of base curvature B when power addition A is constant, and an increasing function of power addition A when base B is constant.

The distance vision zone extended least between two straight lines each making an angle of 15° to 25° with a horizontal line intersecting at a point G situated close to a geometrical centre O of said lens. (Fig. AI.61a). The table AI.3 below gives the width in millimetre of the near vision portion as a function of power addition (A) and base curvature (B) for an example given. The width is given in mm.

TABLE AI.3

The values in table AI.3 are given for a near vision portion width, which is set 12 mm below the geometrical centre of the lens at a control point P.

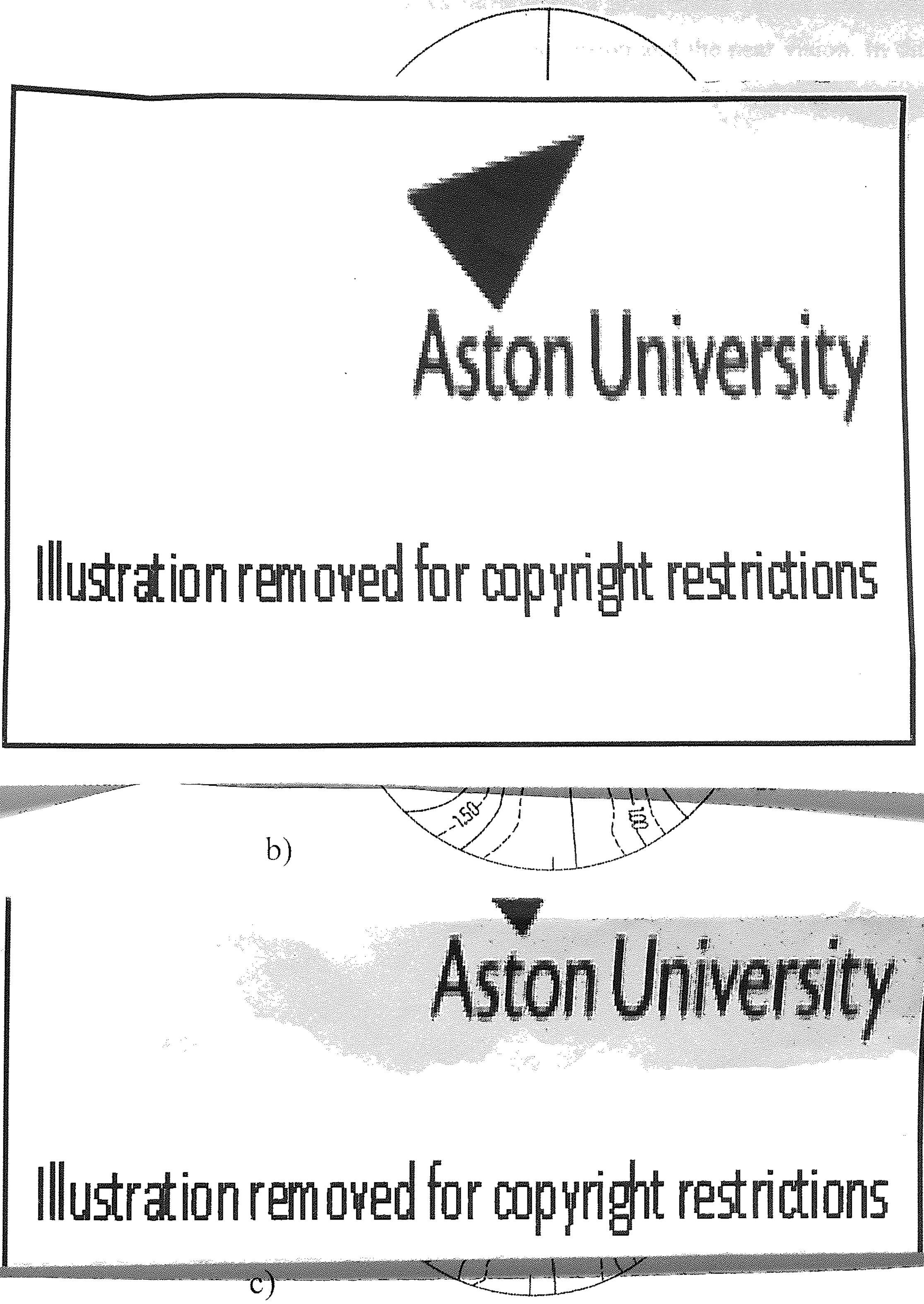


Figure AI.61 *Ahsbahs, et al. progressive multifocal ophthalmic lens. a) Is a front view of the lens having 2.00 Add, for a base of 3.75 D, showing the principal meridian of progression and lines joint points having the same cylinder. b) Is a front view of the lens having 2.00 Add for a base of 5.5 D, showing the principal meridian of progression and lines joint points having the same cylinder. c) Is a front view of the lens having 2.00 Add for a base of 6.5 D, showing the principal meridian of progression and lines joint points having the same cylinder (From Ahsbahs, 1998)*

Kitani (1998) on behalf of Hoya introduced a progressive power lens designed by giving great importance to the intermediate vision and the near vision. In this way a broad intermediate vision zone and near vision zone was ensured. In such lens design, the resultant image of the viewing object was little fluctuated, especially, in lateral directions.

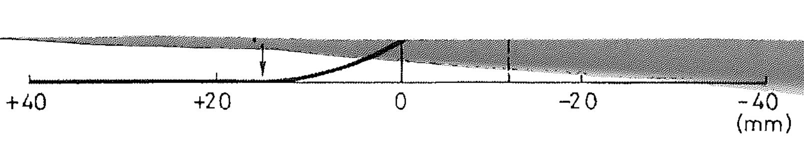
The lens was made such that at the eye-point position E the addition power reached about 30% to 50% of its value. The lens had no axis of symmetry; it was actually a "design of the laterally asymmetric type". More specifically the eye-point position E was located closer to the nose than the far vision power measuring position F, and the near vision power measuring position N was further situated closer to the nose than the eye-point position E in such a manner that both cases of the lens for the right eye and the lens for the left eye are adapted to the convergence action of the eyes

The far vision power measuring position F was located upwardly from the eye-point position E by a distance of 10 to 17 mm (preferable 12 to 15 mm), while the near vision power measuring position N was located downwardly from the eye-point position E by a distance of 14 to 21 mm (preferably 16 to 19 mm). The distance vision zone, in which astigmatism is not more than 0.5 D irrespective of the value of the addition, extended in an area, which made angles 30° and 150° relatively to the line passing from the far measuring point F.

The principal meridian in such lens design had a horizontal deviation H of an arbitrary point P as shown in Figure AI.62b towards the nose relative to the far vision power measuring position F is given by:

$$H = K * Dp/Di$$

where K designates an arbitrary constant satisfying an inequality relation: $1 \leq K \leq 4$. Dp is the additional power at the arbitrary point P and Di the addition of the lens. According to Kitani, the wearing test conducted revealed that for far vision, the astigmatism accepted by wearers was less than or equal to 0.75 D while for the near vision, the astigmatism was about 0.75 D to 1.00 D. According to the above, it is unreasonable to use the same value of maximum astigmatism accepted by wearers for the far vision and the near vision zone.



b)

Add(Di) = 2.00 D

c)

Figure AI.62. *Kitani's progressive power lens. a) Is a diagram of the progressive power lens for the right eye. b) Is a graph for showing the deviation H at an arbitrary point P on the principal meridian of the lens for the right eye of Fig. a). c) Is a diagram showing the astigmatism spread on the lens surface (From Kitani, 1998)*

Isenberg (1998) produced for Optical Radiation Corporation a progressive addition lens, with reduced visual astigmatism. The power curve of the lens was continuous, and was defined by a polynomial of at least the 11th degree.

In a numerical example given the length of the progressive corridor, was about 15.2 mm. The minimum corridor width between 0.5 D contours was about 2.8 mm. The improved lens design presented a 39% reduction in astigmatism peak magnitude (3.01 vs 5.04 D) when compared to a lens constructed using a confocal hyperbolic spreading function and lacking a superposed asphere. More precisely, the lens was characterized by a wide clear distance vision zone, a near vision zone and an improved intermediate zone with reduced aberration density and lowered peak astigmatism.

Surface astigmatism in the intermediate region was reduced by virtue of the improved curvature of the particular functional form of the spreading function proposed. Visual astigmatism was compensated, by superposing an aspheric function over the mathematically defined sag of the lens. Figure AI.63 shows a comparison between a prior art lens design and the one proposed by Isenberg related to the surface astigmatism.

Prior art

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Figure AI.63. *Isenberg's progressive addition lens. Isocontour plots of surface astigmatism are demonstrated of the lens according to Isenberg's design and prior art for comparison (From Isenberg, 1998)*

Ahsbahs, et al. (1998) again for Essilor proposed a new definition of the characteristics of the lens surface to be considered. This new definition makes it possible to improve lens performance as perceived by the spectacle wearer in the near vision region, as well as the gentleness of transition in the intermediate vision region, this new definition preserved an extended far vision region which is acceptable to the spectacle wearer.

The new definition characterizing such a lens design is a power addition factor A. According to such a factor, the isocylinder line joining points having a mean cylinder of A/2 dioptres substantially defines the limit of the far, intermediate and near vision regions. Compared to the prior art limits, which adopted absolute values that were independent of the power addition factor, this definition corresponds better to the reality as actually perceived by the spectacle wearer.

With such a constrain, the criteria for a relative gentle progression were the slope of the mean sphere along the meridian, the length of progression and the width of the intermediate vision region.

In such design the far vision zone consisted of an angular sector (angle $\alpha \geq 145^{o}$) having an apex at the geometrical center of the lens (0) (Fig. AI.64). Also at the intermediate vision region, the relation represented each point along the main meridian

$$\mathbf{p(y)L_p / l_A/2\ (y) < \lambda A}$$

where, p(y) is the slope of the mean sphere at a point y on the y-axis, L_p is the length of progression, and $l_A/2$ (y) is the width of the intermediate vision region at the point y, λ is a coefficient having a value between 0.125 and 0.15 mm^{-1} . Also at point y on the y-axis 18 mm below the fitting centre of the lens, the following relation holds

$$\mathbf{l_A/2A_{VP} / C_{VP} > 14\ mm}$$

where, A_{VP} is the relative power addition, equal to a difference between mean sphere at a point on the main meridian of progression 18 mm below the fitting centre and mean sphere at the fitting centre, while C_{VP} is the maximum cylinder of a horizontal segment extending over the surface of the lens.

Also other characteristics of the design were, that the bisector of angle α made an angle β with the vertical, which was less than 2^{o}, the length of progression L_p was defined as the vertical distance between the fitting centre and the point in the near vision region at which the power addition reached 85^{0} of its maximum value, while the fitting centre was located 4 mm above the geometrical centre of the lens.

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Figure AI.64. *Ahsbahs, et al. progressive lens. It shows a front view of the, for a power addition factor of 2 D, showing the spread of astigmatism, angle α and β. (From Ahsbahs, 1998)*

A progressive ophthalmic lens was presented by *Winthrop (1998)* for American Optical, which was a linear composite of a hard lens design and a soft lens design. The resulting lens design combined features of the visual utility of a hard lens design with the visual comfort of a soft lens design.

The lens had, a distance portion, a reading portion and an intermediate portion, while the composite progressive power surface Z_C was defined by the equation:

$$Z_C^{(A)} = Z_H^{(A-B)} + Z_X^{(B)} - Z_H^{(0)}$$

where:

Z_C =elevation of the progressive power surface above a reference plane,

Z_H =elevation of the progressive power surface above the reference plane for a first design component of the lens,

Z_S =elevation of the progressive power surface above the reference plane for a second design component of the lens,

A=the power addition of the composite lens,

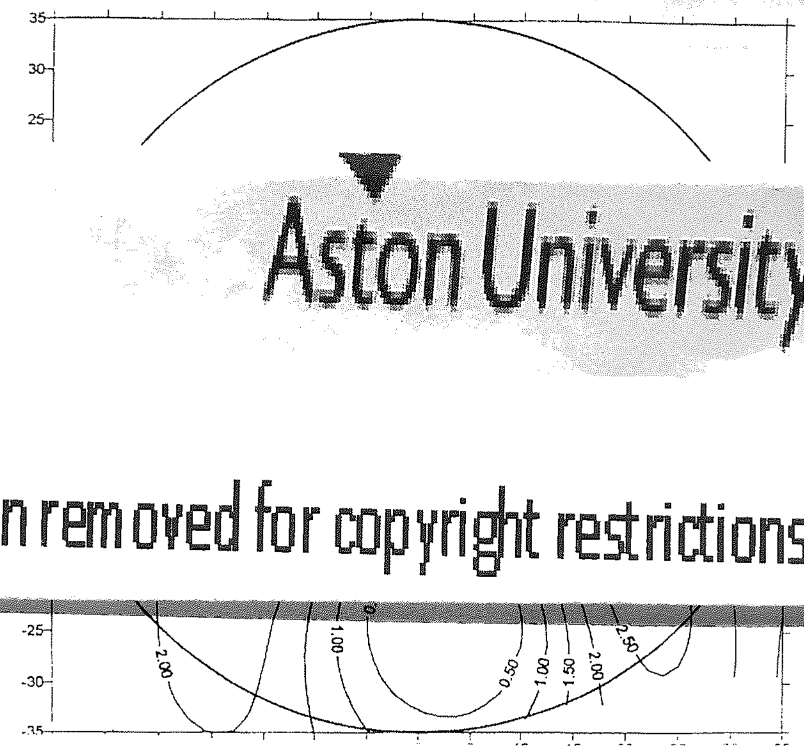
B=the power addition of the second design component.

The hard lens design chosen had an Add equal to A-B while the soft design had an Add equal to B. In order to avoid a doubling of the elevation due to the base curves of the two designs a third design of the hard type with zero Add is subtracted from the composite lens design. Also there has been a limit to the Add used for the soft lens design. According to Winthorp in order to have a final acceptable design especially for the aberrations presented in the far vision portion due to the soft design the maximum Add used for such a soft design should not be more than 1.25 D.

In the example given by Winthorp there is a reduction of minimum 27% in the surface astigmatism presented by the composite design compared with the hard lens design used. A formula was given about the maximum stigmatism presented by the composite design

$$A_{(max)} = 1.5A - 0.75B$$

Where A and B represent the addition of the hard and soft lens design used. The astigmatism plot of a lens made according to Winthorp's design showed very little astigmatism above the 0-180 degree line. This is a characteristic presented only by hard progressive lens designs. Also, the maximum surface astigmatism was less than 2.00 D and the gradient of astigmatism was less than 0.20 D/mm, values characteristic of soft lens designs. Of course the lens was asymmetrical with respect to the corridor of the principal meridian to ensure binocular compatibility of the lens pair.



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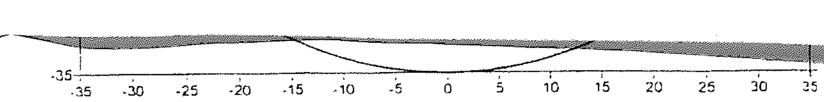

SOFT DESIGN

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Figure AI.65. *Winthrop's Hard/soft superposition progressive lens design. a) Shows, the surface astigmatism power plots for a hard design with Add 2.00 D. b) shows, the surface astigmatism power plots for a soft design with Add 1.25 D. c) shows, the surface astigmatism power plots for a hard design with Add (A-B) 0.75 D. d) shows, the surface astigmatism power plots for a composite design with Add 2.00 D. (From Winthrop, 1998)*

A progressive spectacle lens was described by *Barth (1998)* for Optische Werke G. Rodenstock with a convex, aspherical front surface and a concave back surface having aspherical regions. The idea was to transpose the irritating surface astigmatism of the progressive front surface into an area where the power does not increase, this area being the zone for distance vision.

The lens possessed surfaces whose main meridians were formed as umbilical lines and where the astigmatism presented by the first progressive surface was compensated for by the astigmatism of the opposing surface. With such a construction a distance portion, which was practically completely free of astigmatism and which was actually afocal was produced when the two surfaces in the area of the distance portion have a substantially matching construction. The lens according to the inventor was suitable for the so-called emmetropic presbyopes.

Figure AI.66a shows a cross-section of such a lens concept. The front surface (1) is a progressive surface, where the power increases from the distance portion (3) over the progression area (4) to the reading portion (5). The back surface (2) of the lens in the area (6), opposite to the distance portion (3) is designed so that its surface astigmatism compensates the surface astigmatism of the front the distance portion (3). Surface (6) is connected via a narrow transition area (7) with a spherically designed zone (8).

Figure AI.66b shows the surface astigmatism of the front surface (1) the surface was design such as the surface astigmatism, particularly in the distance vision zone to be very high outside the main meridian. At the progression, from y=+6 to y=-14 mm, the surface astigmatism was small and less than 0.50 D in the reading vision zone. B_F and B_N were the distance and near reference points. Area (6) of the back surface possessed a surface astigmatism value, which was opposite and equal to the surface astigmatism of the distance portion (3). So the total astigmatism of such a progressive lens is shown in Figure AI.66c. As Figure AI.66c shows, the distance and near vision zones were free of astigmatism but the zone at the progression corridor presented surface astigmatism.

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a)

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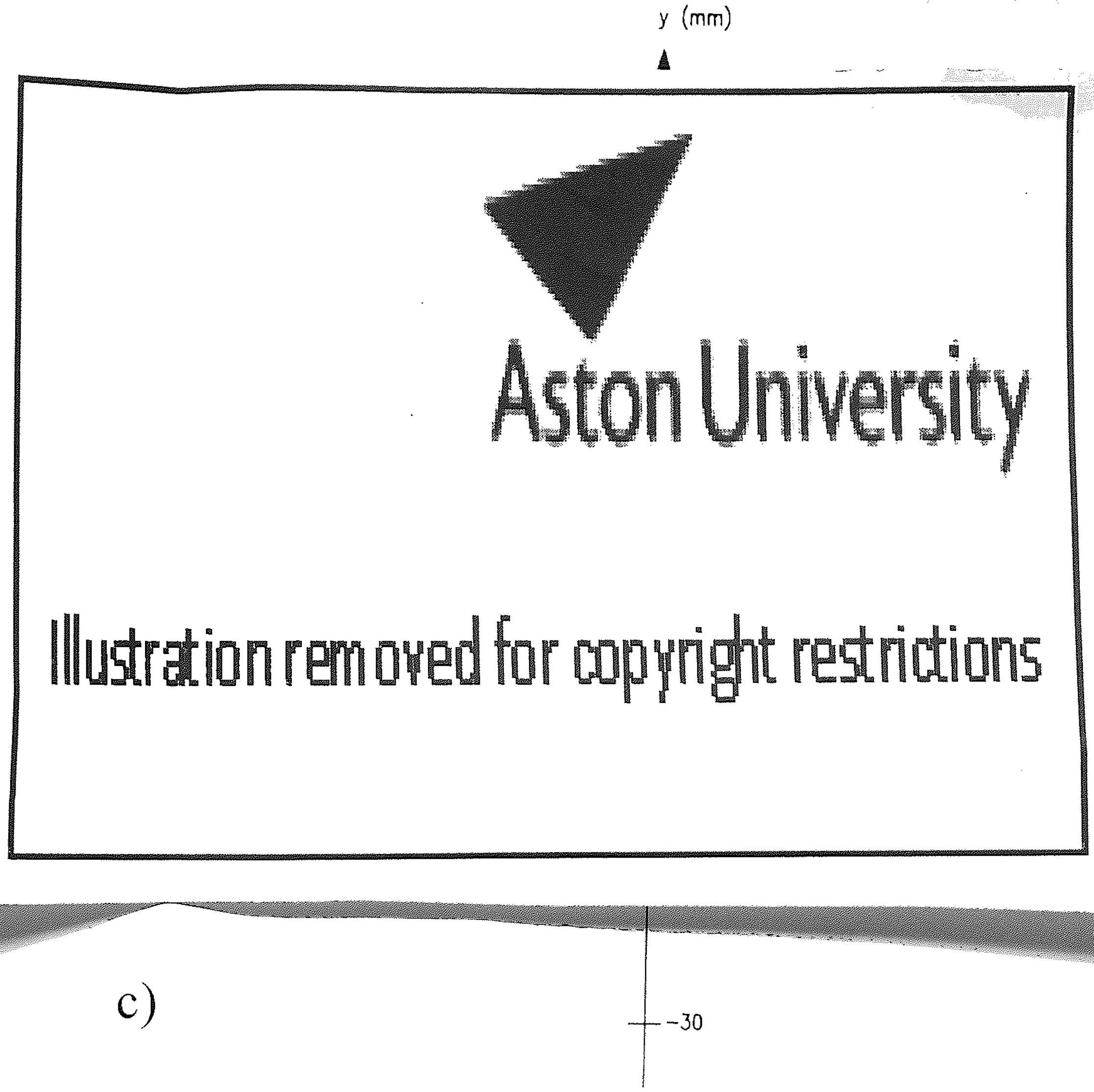
b)



c)

Figure AI.66. *Barth's progressive spectacle lens. a) Shows a cross-section of the lens. b) Illustrates the surface astigmatism for the front surface of such a lens. c) Illustrates the total astigmatism presented by such a lens (From Barth, 1998)*

A multifocal spectacle lens was proposed by *Kelch, et al. (1998)*. The special feature of such a lens is the combination of the most important characteristics of a multifocal lens, such as, an extraordinary width of the progression channel with a gentle increase of the astigmatism laterally of the progression channel and a not too intense drop of the average power laterally of the progression channel and of the near zone. Furthermore, the lens had a correct position for convergence in the entire progression channel. These improvements are achieved in the entire given addition range and for all spherical and astigmatic far zone properties of the region for the far-reference point from -4 dpt to +4 dpt in the absolute strongest principal section (stH), a cylinder of 0.0 to 4.0 dpt and an addition (ADD) of 1.00 to 3.00 dpt.

The invention is especially advantageous for short progression zones. A reduced maximum value for the astigmatic deviations in the centre regions of the spectacle lens is advantageous. The lens also had a centre cross and a measurement point disposed 4 mm vertically below the centre point.

The front surface was an aspheric nonaxial symmetric multifocal surface, which was differentiated continuously at least twice. All the above features were within an elliptical region on the surface of the lens extending 50 mm measured horizontally and 40 mm measured vertically from the measurement point.
The predetermined region having a minimum channel width (in millimetres) measured horizontally is shown in the following table AI.4:

Table AI.4

stH/ADD	**1.0**	**1.25**	**1.50**	**1.75**	**2.00**	**2.25**	**2.50**	**2.75**	**3.0**
-4.00	**15.1**	**10.8**	**7.9**	**5.9**	**4.7**	**4.1**	**3.8**	**3.5**	**3.0**
-3.00	**14.9**	**10.7**	**7.8**	**5.9**	**4.7**	**4.1**	**3.8**	**3.5**	**3.0**
-2.00	**14.3**	**10.4**	**7.6**	**5.8**	**4.7**	**4.1**	**3.8**	**3.5**	**3.0**
-1.00	**13.3**	**9.8**	**7.4**	**5.7**	**4.7**	**4.1**	**3.8**	**3.5**	**3.0**
.00	**12.2**	**9.2**	**7.1**	**5.6**	**4.7**	**4.1**	**3.8**	**3.4**	**3.0**
+1.00	**11.0**	**8.5**	**6.7**	**5.5**	**4.6**	**4.1**	**3.7**	**3.3**	**2.9**
+2.00	**9.8**	**7.8**	**6.4**	**5.3**	**4.5**	**4.0**	**3.6**	**3.2**	**2.7**
+3.00	**9.8**	**7.3**	**6.0**	**5.1**	**4.4**	**3.9**	**3.4**	**3.0**	**2.6**
+4.00	**8.3**	**6.8**	**5.7**	**4.8**	**4.2**	**3.7**	**3.3**	**2.9**	**2.5**

As it shows from the table this minimum width, was dependent upon the strongest principal section (stH), in the far-reference point, and the addition (ADD).

The dioptric power in the progression zone was essentially linear along the principal viewing line for a length of 11 mm where 75% of the addition (ADD) was reached. The maximum astigmatic deviation Amax in dpt was given by the following equation for ADD $\leq$ 1.50 dpt:

$$\mathbf{Amax \leq (1.13+0.070*stH+0.016*stH^2)*ADD}$$

and, the maximum astigmatic deviation Amax in dpt for ADD $\geq$1.75 dpt is given by the following equation:

$$\mathbf{Amax \geq (1.16+0.025*stH+0.004*stH^2)*ADD}.$$

Such a muiltifocal lens is provided with a so-called thickness reduction prism having a size, which is dependent upon the addition and having a base position of 270^o. Preferably, the following table AI.5 is used for determining the values to be utilized.

Table AI.5

Add (dpt)	**1.00**	**1.25 and 1.75**	**1.50**	**2.0**	**2.25 and 2.50**	**2.75**	**3.00**
Prism (cm/m)	**0.50**	**0.75**	**1.00**	**1.25**	**1.50**	**1.75**	**2.00**

This prism serves not only to correct an angular vision defect, but is intended to ensure that the peripheral thicknesses above and below are approximately the same.

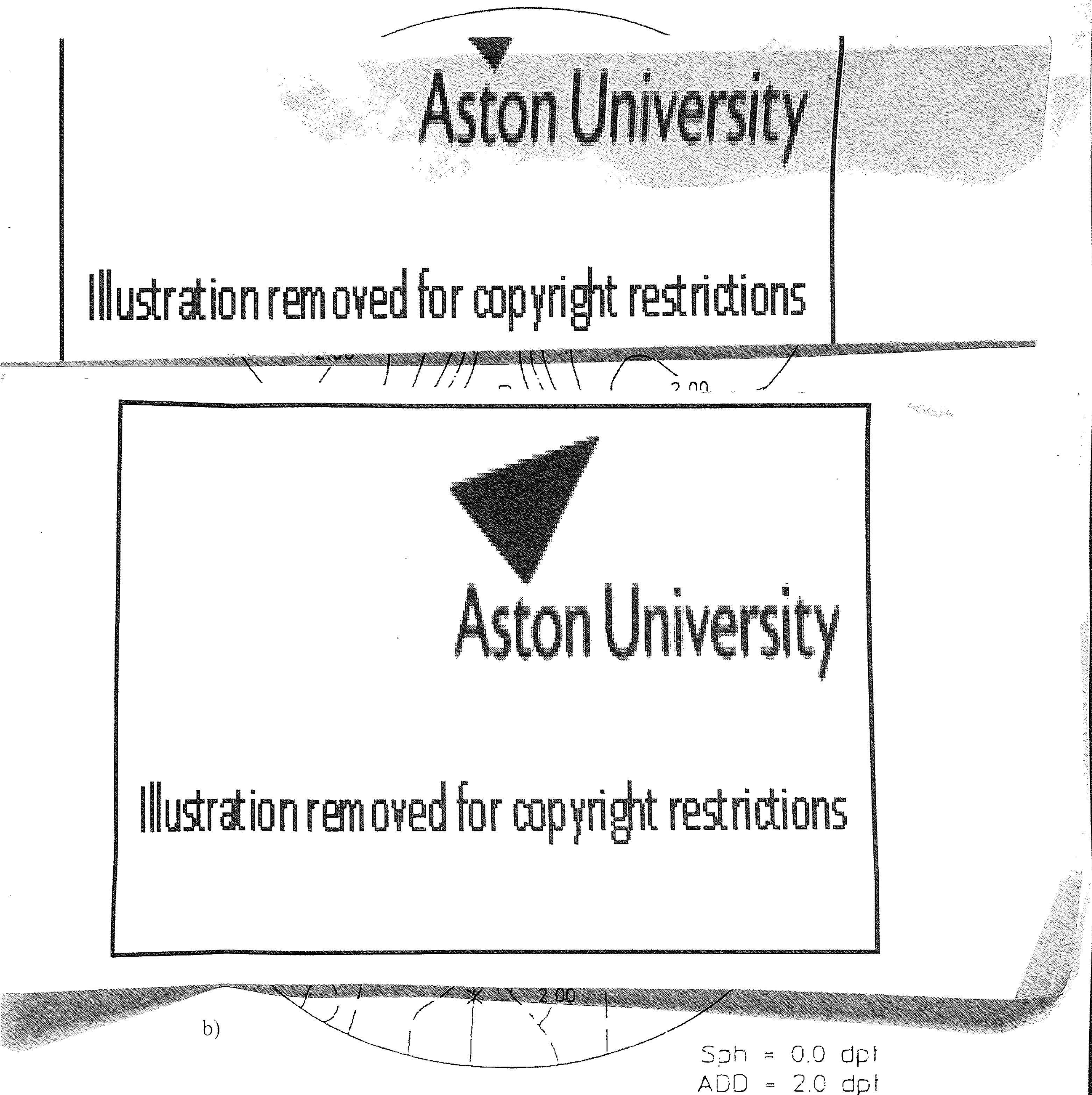


Figure AI.67. *Kelch, et al. multifocal spectacle lens. a) Shows the elliptical measuring zone of the lens showing the astigmatic deviations. b) Shows, within the elliptical measuring zone, the increase of the average power of the lens. (From Kelch, 1998)*

Umeda, et al (1998), for Nikon introduced a progressive lens, where its object was to provide a progressive lens for the near work in which a sufficiently wide clear vision area is disposed in the near viewing area and yet the width of a clear vision area equivalent to that in a progressive lens for general life is secured in the intermediate vision area and where the far vision area was sufficiently wide for use.

The principal meridional line between the far viewing centre of the far vision area and the near viewing centre of the near vision area was within 18 mm, and the width of the clear vision area in the near viewing area was greater than the width of the clear vision area in the far viewing area. Also, the maximum width of the clear vision area in the far viewing portion was at least double the minimum width of the clear vision area in the intermediate viewing portion. Since the length of the progressive zone is within 18 mm, the angle of rotating of the eyeball becomes small and the feeling of fatigue is little

The value of the maximum astigmatic difference presented by the lens was smaller than the addition. The value of the maximum astigmatic difference was 75% of the addition (equivalent to that in the balance type of the progressive lens for general life). Further, the width of the clear vision area in the intermediate vision area was about 5 mm.

As it is seen from Figure AI.68 the far viewing centre OF is located 12 mm above the geometrical centre OG of the lens, and the near viewing centre ON is located 4 mm below the geometrical centre OG. That is also, the length of the progressive zone of about 16 mm. Also, the additional refractive power at the geometrical centre OG is 75% of the addition, i.e., 1.50 dioptre.

Figure AI.68. *Umeda, et al, Progressive lens. a) Shows a typical equi-astigmatic line chart in such a progressive lens (From Umeda, 1998)*

The progressive addition lenses produced by *Roddy (1998)* comprised distance and near zones with generally spherical base curves, wherein the distance and near zones are connected by areas having aspheric base curves. These aspheric connecting areas are referred as connecting wedges and zones of inflection elimination (ZIE).

Generating a toroidal surface produced the connecting wedges. The toroidal surface had isocylindrical values with the astigmatism zones corresponding to their respective intermediate and near zones, zones of inflection elimination.

Filling the connecting area with a smooth surface that abuts to the top and bottom portions of the zones without creating inflection points or lines produces the connecting wedges. This design does not need to have a specific geometric definition.

This design provides a lens, which is cosmetically appealing and optically acceptable by the patient. These advantages are accomplished by making the intermediate zones with preferably a finite number of addition steps, designing the lenses with generally spherical sections which combine to form a unique aspheric surface, providing thus acceptable power change in the distant-intermediate or intermediate-near junction zones.

The distance zone had an isocylindrical value of about 0.00 dioptres and a constant isospherical equivalent; providing an intermediate zone with a full intermediate add power from about 8° to about 28° of ocular depression. This provides an intermediate zone with a usable add width of about 48°; providing a full near add power at about 28° of depression and a near add width of about 108°.

Figure AI.69 illustrates a front lens surface of such a design, wherein the lens includes a distance zone, intermediate zones, a near zone, connecting wedges, zones of inflection elimination (ZIE) and an aspheric fringe.

Figure AI.69. *Roddy's ophthalmic no-line progressive addition lenses. The diagram illustrates a front lens surface, wherein the lens includes a distance zone, intermediate zones, a near zone, connecting wedges, zones of inflection elimination (ZIE). (From Roddy, 1998)*

Altheimer, et al. (1998) on behalf of Rodenstock described a series of progressive lenses. In such a lens design dimensioning rules were proposed for the parameters which are essential from a physiologic point of view in a lens, such as the delimitation of the distance-vision part and the error in alignment of the primary line, by which this line follows the point at which the line of vision, with eyes dropped, passes through the progressive surface.

The lens had a maximum height y (in mm) of the line on which the surface astigmatism is 0.5 dpt and which hence delimits the suitable area of clear vision on either side of the primary line at a distance of 25 mm. The maximum height y is given by the equation

$$y=f(Add,BK)=b(BK)+a/Add*1000)$$

$$b(BK)=a_0+a_1*BK+a_2*BK^2$$

The coefficients on the nose side and the temporal side of the primary line are defined as shown at the next table AI.6.

Table AI.6

	nose side	temporal side
a	-8.5 ± 20%	-7.5 ±20%
a_0	18...19 mm	19...20
a1	-3580 ±29% mm^2	-4520±20% mm^2
a_2	390 000 ± 20% mm^3	480 000 ±20% mm^3.

The lines of equal surface power were horizontally passing over into the primary line, which is different from prior art. With this provision rocking phenomena etc. are definitely avoided for the wearer of the eyeglass in the event of a horizontal sighting movement. The horizontal passage of the lines of equal surface power into the primary line is achieved by the definition of an infinitesimal strip of a higher order on either side of the primary line.

According to the invention it has been found that the surface on the concave side should be made aspherical providing substantial cosmetic advantages. In fact, an aspherical surface permits the achievement of an enlargement of the area suitable for clear distinct vision.

SURFACE PROPERTIES spec. n=1.604 astigmatism [dpt]
BASE GRAPH 4
Sph = −2.50 ADD = 1.00 n = 1.604 drpr = 0.00
y [mm]

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−30 −20 −10 0 10 20 30
.50
1.00
x [mm]

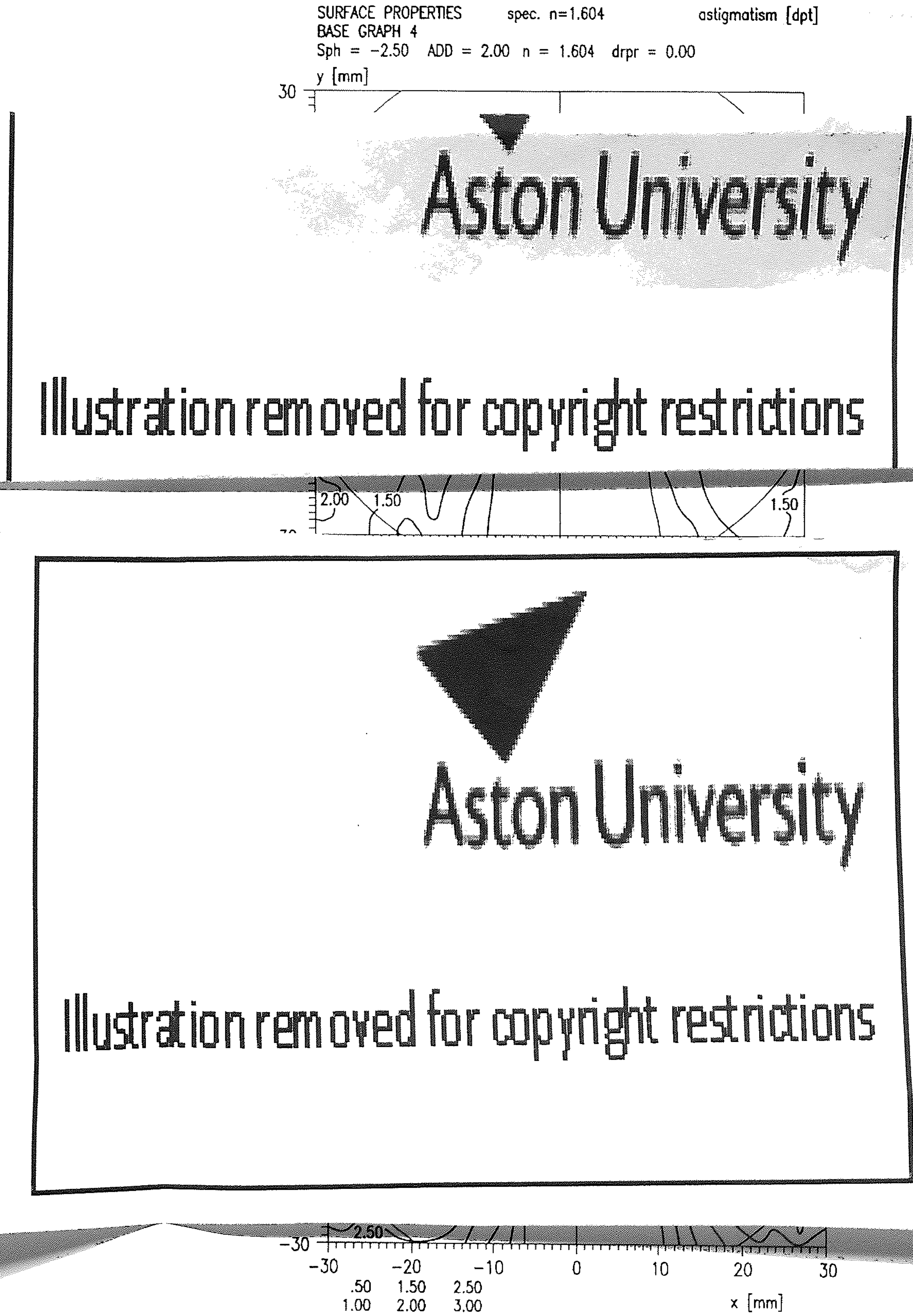


Figure AI.70. *Altheimer, et al. Series of lenses. The diagrams show each lines of equal surface astigmatism for lenses having a surface power of 4 dpt at the distance-vision reference point, and different additions (1 dpt to 3 dpt). (From Altheimer, 1998)*

An optical lens or semi-finished lens blank was provided by *Blum, et al, (1999)* for use as a multifocal lens. It comprised a composite of at least three different and separately applied layers, each layer having a different refractive index, which allow for a progressive multifocal lens having a wide and natural progression of vision when looking from far to near. The lens is claimed to be substantially free of unwanted peripheral astigmatism, incorporating a wide reading zone, easy to fit a patient and possesses a cosmetic appearance, which is mostly invisible.

Figure AI.71 shows such a lens having a base layer with a first refractive index and a region of varying thickness, an outer layer having a second refractive index different from the first refractive index and a transition zone comprising at least one layer bonded between the base and outer layer, each of the layers having a different refractive index and which differs from the refractive indices of the base layer and the outer layer wherein the refractive index of each of said at least one layer is substantially constant throughout the layer and the transition zone has an effective refractive index which is approximately the geometric mean of the refractive indices of the base and outer layer.

Figure AI.71. *Blum, et al, Refractive index gradient lens. (From Blum, 1999)*

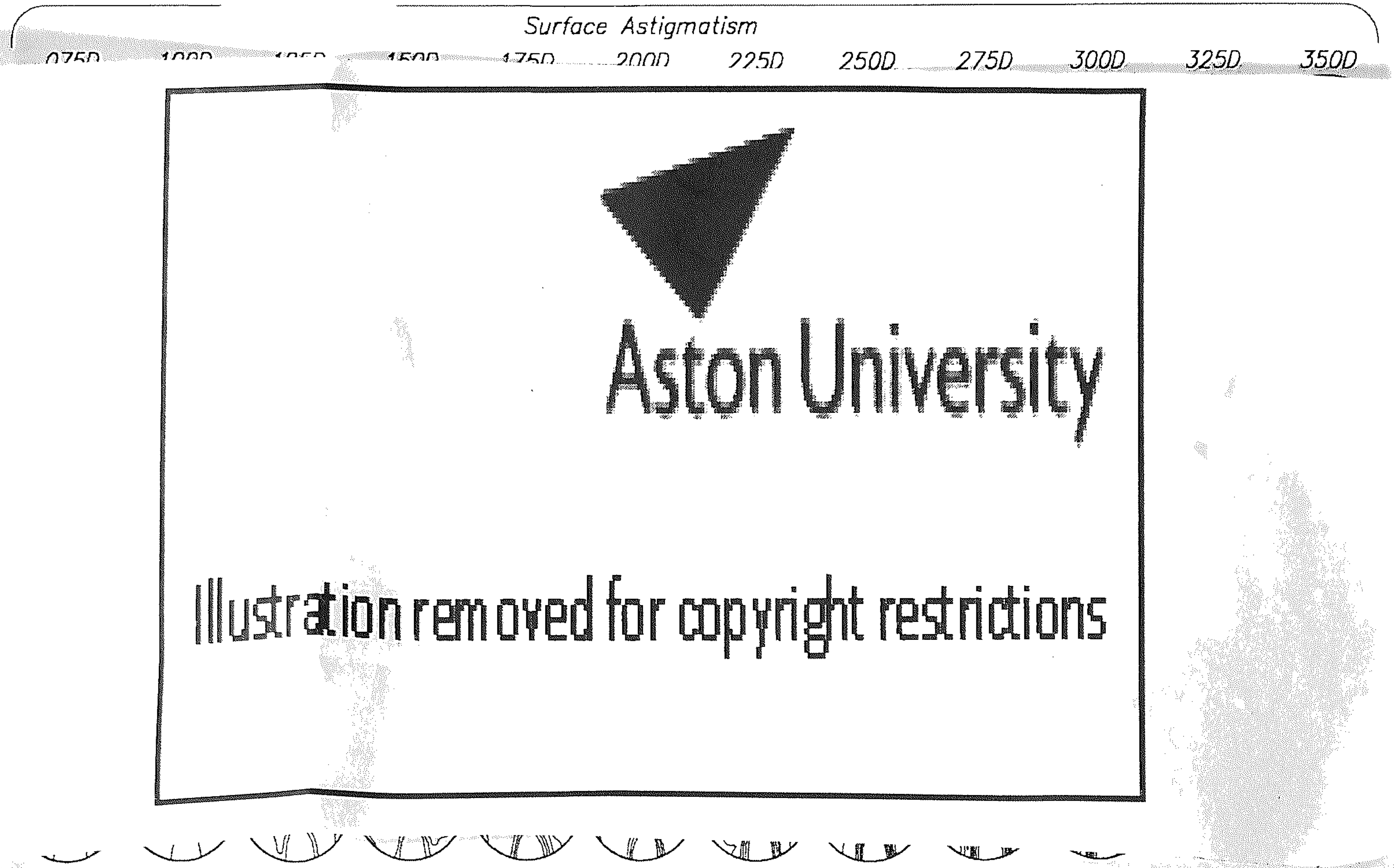
Morris, et al (1999) for Sola introduced a series of progressive ophthalmic lens designs.

The progressive ophthalmic lens series including a first set of lens designs having at least one base curve suitable for use in providing a range of distance prescriptions for myopes, and a second set of lens designs having at least one base curve suitable for use in providing a range of distance prescriptions for emmetropes and hypermetropes, each set containing elements with different addition powers. These lens designs from different sets had substantially the same addition power and substantially the same optical field of vision in the lower viewing zone.

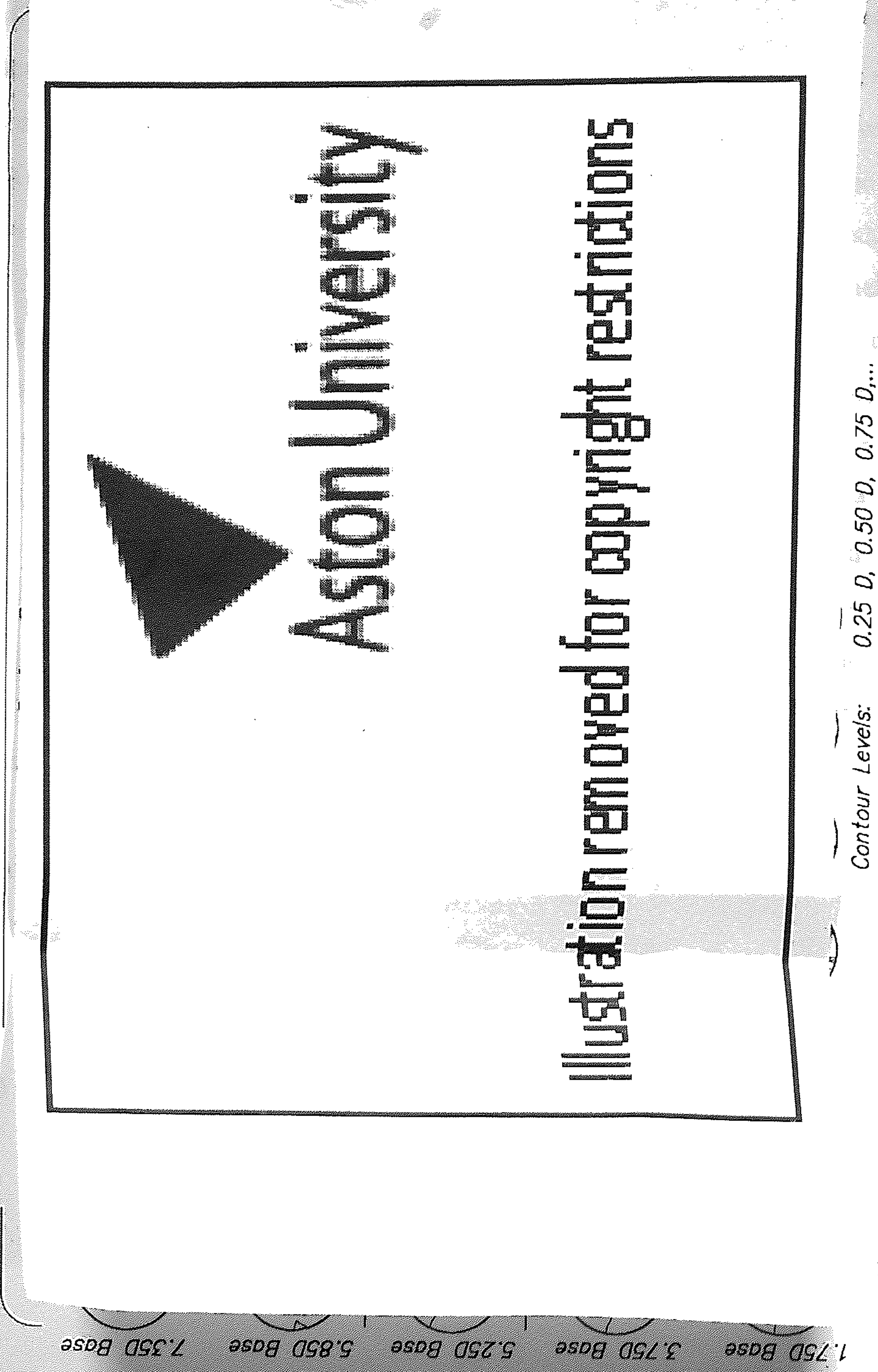
In such a lens series the corridor length varies from relatively long at low addition powers to relatively short at addition powers of approximately 3.00 dioptres (D) and then to a medium length at addition powers greater than 3.00 D. For example, the corridor length may vary from approximately 19.00 mm to approximately 17.50 mm as addition power increases from 1.00 D to 3.00 D, and then increases to a value of approximately 18.25 mm above 3.00 D.

Also the width of the near vision zone may vary from relatively narrower at low addition powers to medium at high addition powers. For example, the horizontal width of the near viewing zone, measured from the temporal 0.50 D astigmatic contour along a horizontal line to the nasal 0.50 D astigmatic contour may be approximately 15.00 mm at the vertical height of -22.00 mm from the geometric lens centre for a 1.00 D addition power. The horizontal width of the near viewing zone, measured from the temporal 1.00 D astigmatic contour along a horizontal line to the nasal 1.00 D astigmatic contour may vary from approximately 15.25 mm at the vertical height of -22.00 mm from the geometric lens centre for a 2.00 D addition power to approximately 16.00 mm for a 3.00 D addition power.

a)



Surface Astigmatism
225D 250D 275D 300D 325D 350D
Contour Levels: 0.50 D, 1.00 D, 1.50 D,...



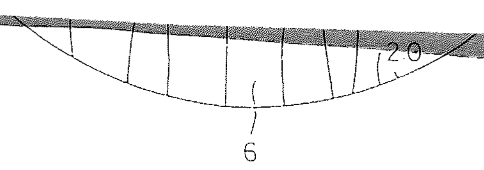
b)

Figure AI.72. *Morris, et al progressive lens series. a) Illustrates a series of contour plots of surface astigmatism for a series of progressive lenses. The contour plots are broken into three sets: for Hyperopes, Emmetropes and Myopes, respectively, reading from the top of the figure. The numbers given for each plot refer to base curve and Addition Power respectively. b) Illustrates a series of contour plots of mean surface power for a series of progressive lenses as illustrated in Fig. a). (From Morris, 1999)*

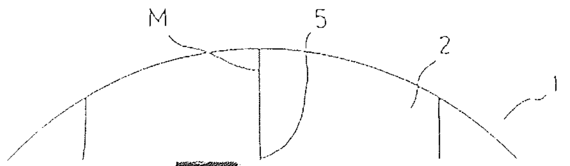
Kaga, et al. (1999) for Seiko Epson Corporation, in a process to determine the surface shape of each of progressive multifocal lenses for use as lenses in eyeglasses, radii of curvature at main points were calculated, and then the surface was divided into a plurality of lattice sections. Then a curved-surface equation in the form of a bicubic expression was used for each section to determine the surface shape of the lens. A coefficient of each of the bicubic expressions was determined under a condition that continuation was established to curved-surface equations of sections adjacent at a boundary line between the sections to the derivatives of second order. Therefore, the surface shape of the lens obtained by the curved-surface equation for each section could be formed into a continuous and smooth surface. Since the curved surface could be determined for each section, a partial correction could easily be performed, if necessary. As a result, a progressive multifocal lens was provided which exhibits smooth astigmatism curves and a large clear field of vision to meet a variety of specifications. Thus, lenses for eyeglasses each having a clear field of vision was provided.

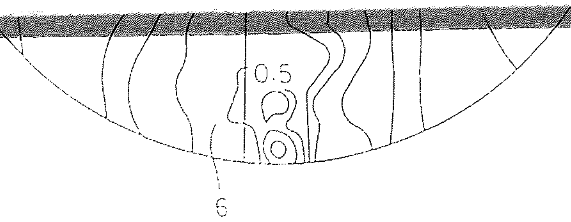
The curved-surface equation for such a lens is determined for each section in accordance with the corrected curvature radius. In this patent, the following bicubic expression is employed as the curved-surface equation.

$$f_{ij}(x,y) = \sum_{m=0}^{3} \sum_{n=0}^{3} C_{m,n}(x-x_1)^m (y-y_i)^n$$



a)





b)

Figure AI.73. *Kaga, et al. progressive multifocal lens. a) Shows astigmatisms of a progressive multifocal lens manufactured by using 3 mm x 3 mm lattice sections according to the invention. b) Shows astigmatism of a progressive multifocal lens manufactured by using 4 mm x 4 mm lattice section according to the invention. (From Kaga, 1999)*

Ueno, et al. (1999) on behalf of Nikon provided a progressive multifocal lens. Such a progressive multifocal lens enables people with even greatly weakened eye accommodation ability to comfortably continue to see short distances for a long period of time without eyestrain. The lens had a near part N, a defined vision part F for distance, and an intermediate part P along the main meridian curve MM'. The special feature of the lens was that the near centre B of the lens is separated from near eye point E by a distance of substantially 2 mm to 8 mm in the lower part along the main meridian curve as it is seen in Figure AI.74a. The refractive power K_E at the near eye point, refractive power K_A at the defined centre A, and refractive power K_B at the near centre B satisfies the condition:

$$\mathbf{0.6<(K_E - K_A)/(K_B - K_A)<0.9.}$$

where:
K_E is the refractive power at the near eye point,
K_A is the refractive power at the centre of the second zone, and
K_B is the refractive power at the centre of the first zone.
The lens also satisfied the following conditions

$$\mathbf{W_F \geq 50/(K_B - K_A)}$$
$$\mathbf{W_N \geq 50/(K_B - K_A)}$$

where:
W_F is the maximum width in millimetres of the clear vision zone in the far vision zone, and
W_N is the maximum width in millimetres of the clear vision zone in the near vision zone.

According to the invention, the rate of increase in the longitudinal curvature value from the bottom portion to the top portion of the far vision zone decreases heading from the bottom portion toward the top portion. The position where the longitudinal curvature value in the bottom portion of the progressive zone changes from decrease to increase should be only W/3-2W/3 laterally distant from the point of intersection with the main meridian curve, where W is the radius of the progressive multifocal lens.

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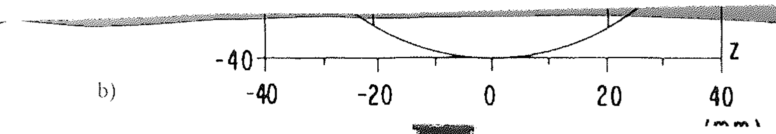

b)

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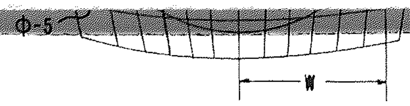


c)

Figure AI.74. *Ueno, et al. progressive multifocal lens. a) Is a drawing schematically explaining the refractive power distribution along the main meridian curve of the progressive multifocal lens. b) Is an equal astigmatic difference curve drawing for the progressive multifocal lens. c) Is a drawing explaining the horizontal cross-section and vertical cross-section for the lens. (From Ueno, 1999)*

Mukaiyama, et al. (1999) for Seiko Epson Corp., provided a multifocal lens, which was provided with progressive refractive surfaces on both surfaces, being the surface on the side of the object and the surface on the side of the eye. In such a lens design the difference of the average surface power of the distance-vision area of the surface on the side of the object and the average surface power of the near-vision area is made mathematically less than the addition power add. Consequently, a multifocal lens was provided, whereby a comfortable visual field could be obtained, in which there is little jumping and warping of images due to the difference of magnification, and furthermore, the clear-vision area having improved astigmatic aberration is wide, and there is little jumping of images.

The average surface power D11 of the first visual field area of the surface on the side of the object and the average surface power D12 of the second visual field area, and the average surface power D21 of the first visual field area of the surface on the side of the eye and the average surface power D22 of the second visual field area, satisfy the following relationships,

$$-(L \times n/t)Add < D12 - D11$$

$$D21 - D22 = Add - (D12 - D11)$$

where, L is the distance from the vertex in units of meters (m), t is the center thickness of the multifocal lens for eyeglass in units of meters (m), and n is the refractivity of the multifocal lens for eyeglass.

The magnification presented in different parts of the lens was, SM1 of the distance-vision area and the magnification SM2 of the near-vision area and are made such that they approach the following relationships based on equation

$$SM1 = SM2 = 1$$

$$Mp1 \times Ms1 = Mp2 \times Ms2 = 1$$

where Mp is the power factor and Ms is the shape factor.

Thus, for the multifocal lens of the invention, the astigmatic aberration and difference of magnification of the first and second visual field areas can be reduced by adjusting the refractive powers of the first and second visual fields of both the surface on the side of the object and the surface on the side of the eye.

b)

c)

Figure AI.75. *Mukaiyama, et al. Multifocal lens. a) Shows aberration of the surfaces on the side of the object and on the side of the eye of the proposed multifocal lens. b) Shows aberration of the entirety of the progressive multifocal lens. c) Shows the schematic structure of the lens (From Mukaiyama, 1999)*

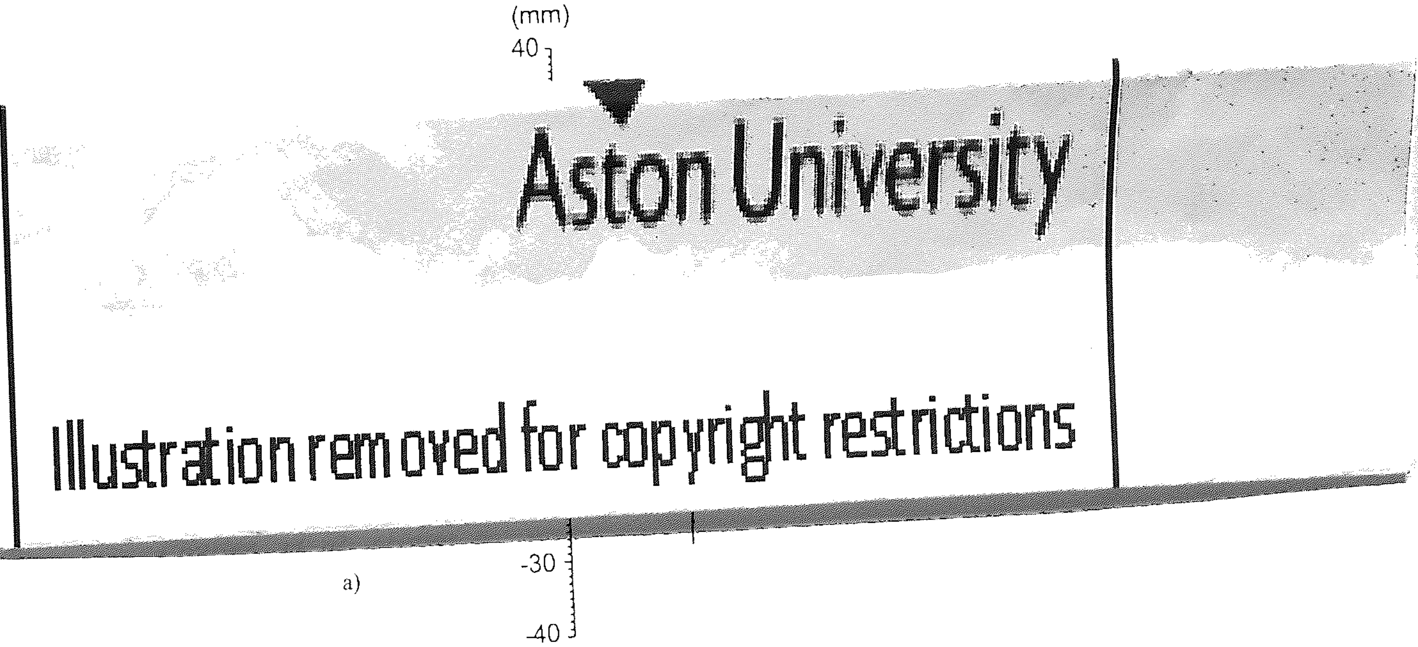
Le Saux, et al. (1999) on behalf of Essilor introduced an improved multifocal lens. The invention provided a multifocal ophthalmic lens ensures that the wearer perceives good visual comfort, a high near vision area and a wide vision field in the near, the intermediate and in the far vision area. It also ensures the wearer enjoys gentle progression in all regions of the lens. The lens had an aspherical surface divided into a far vision region VL, a near vision region VP, an intermediate vision region VI, in which a main meridian of progression MM' passes through the three regions. The principal length of progression is shorter than 16 mm, and the following relation defines the maximum cylinder Cmax inside a 20 mm radius circle centered on a geometrical centre of the lens:

$Cmax/d \leq 0.50 Pmer$

where d is a distance between the geometrical centre of the lens and a point inside the circle where cylinder is at a maximum value and P_{mer} is a maximum slope of mean sphere along the main meridian of progression.

Also the main meridian of progression is made up by midpoints of horizontal segments joining respective lines formed by points where cylinder is 0.50 dioptre.

The lens design is focused to provide very good near vision and intermediate vision, having a power addition defined as a difference between maximum and minimum values of mean sphere on the meridian of progression, inside a 20 mm radius circle cantered on the geometrical centre of the lens. In this case, the principal length of progression is defined as a ratio between power addition and maximum slope of mean sphere on the meridian, and the cylinder within the 20 mm radius circle cantered on a geometrical centre of the lens is less than power addition, and preferably less than 80% of power addition.



a)

Figure AI.76. *Le Saux, et al. multifocal ophthalmic lens. a) Shows graphically the variation in power along the meridian of the lens, for Addition 1.00. b) Is a front view of the lens, showing the main meridian of progression and lines indicating the level of mean sphere. c) Is a front view of the lens, showing the main meridian of progression and lines indicating cylinder level. (From Le Saux, 1999)*

Pfeiffer, et al. (1999) for Rodenstock provided an ophthalmic lens. The surface astigmatism on the main line of the progression had a specific amount and an axial position along the main line in such a manner that the resulting overall astigmatism of the lens, resulting from the geometric addition of the surface astigmatism and an oblique astigmatism, were practically constant or variable along the main line with regard to both the amount and the axial position according to physiological requirements.

The second surface of the lens was an atoric surface of a rotational symmetry and had an astigmatic effect. The overall astigmatism along the main line was constant with regard to amount and axial position also being provided in the region respectively the regions having at least practically a constant optic power. The main line and the region surrounding was characterized by the following performance function

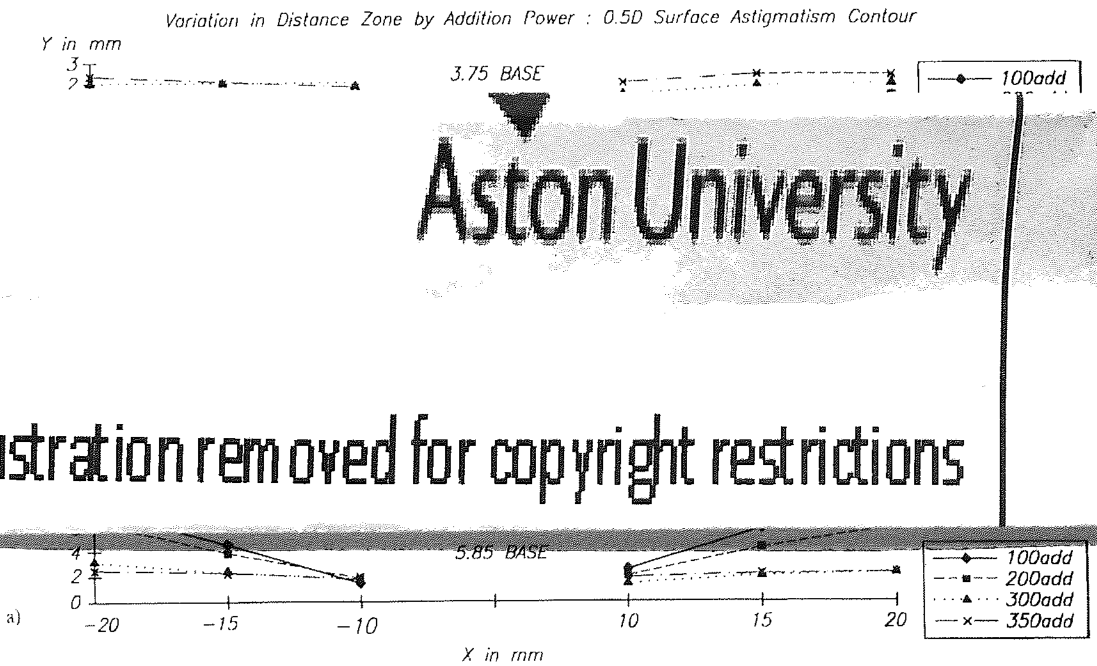
$$F = \int_{Ymin}^{Ymax} [(A - Av)^2 + (H-Hv)^2 + (\varepsilon - \varepsilon v)^2]dy$$

with $A_{.v}$ (y), H_v (y) and $\varepsilon_{.v}$ (y) being the prescribed surface astigmatism, surface power, and axial position of the surface in relation to the horizontal X plane, respectively, and with A(y), H(y), and ε.(y) being the surface astigmatism, surface power, and axial position of the surface in relation to the horizontal x plane, respectively.

Morris, et al. (2000) on behalf of Sola Intern., produced a series of progressive ophthalmic lenses.

The basic concept of these series of lenses is that the visual fixation locus was inset generally horizontally nasally from the fitting cross (FC) of the lens a horizontal distance and extending obliquely down the corridor, the degree of horizontal inset decreasing with increasing addition power. This lens design had at least one base curve suitable for use in providing a range of distance prescriptions for myopes, and one base curve suitable for use in providing a range of distance prescriptions for emmetropes and hypermetropes with different addition powers. The lens design, which had the same addition power, had substantially the same optical field of vision in the lower viewing zone.

More preferably both the horizontal segment at the fitting cross height and the near inset vary to achieve convergence at the required task distance.



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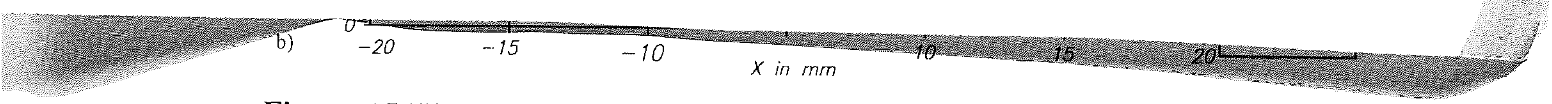


Figure AI.77 *Morris, et al. progressive lens. a) Illustrate, for each of three base curves, the variation in the position or width, in upper or distance viewing zone, of the 0.50 D Surface Astigmatism contour with increasing addition power. b) Illustrate, for each of four addition powers, the variation in the position or width, in upper or distance viewing zone, of the 0.50 D Surface Astigmatism contour with increasing distance power or base curve. (From Morris, 2000)*

Baudart, et al. (2000) for Essilor proposed a multifocal ophthalmic lens. To avoid distortion at the periphery of the lens which this would otherwise occasion, the isosphere and isocylinder lines are distributed over the surface of the lens so as to ensure variations in sphere are not too sudden along a 20 mm radius circle cantered on the geometric centre of the lens and variations in cylinder on the surface of the lens inside this circle are also very small. The lens has an enlarged near vision region and progression is less perceptible to the wearer. The lens ensures improved peripheral vision, while still maintaining good foveal vision performance, thereby facilitating adaptation of wearers to their lenses.

For a progressive multifocal lens, the principal length of progression L_{pp} is defined as a difference in height between the y-axis value of a mounting centre and the y-axis value of a point on the meridian at which mean sphere is equal to the sum of mean sphere at the reference point for far vision, plus 85% of the power addition. In such a lens, mean sphere is 85% higher than power addition at the far vision reference point at a point of value y= -8.4 mm; where a mounting centre is located at a y-axis value of y= 4 mm, the principal length of progression is 12.4 mm.

For a progressive multifocal lens constructed mainly for near and intermediate vision, such as the one proposed here, the principal length of progression is the ratio between power addition as defined above and the slope of mean sphere along the meridian; this can be written as:

$$\mathbf{L_{pp} = (S_{max} - S_{min})/P_{mer}}$$

where S_{max} and S_{min} are respectively the maximum and minimum values of sphere on the meridian, and P_{mer} is the maximum value of the slope of mean sphere along the meridian; slope of sphere corresponds to the maximum modulus of sphere slope with respect to x and/or y. This ratio L_{pp} is equivalent to a length, and represents the length over which mean sphere increases by a value corresponding to power addition.

For lenses of 1 dioptre power addition, the values of maximum cylinder are as follows:

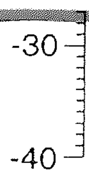
A/P_{mer} =12.4 mm
$|dS/d\theta|max$ /P_{mer} =0.22 and
Cmax 0.88<A_{nom} =1.00 diopters

For lenses of 2 and 3 dioptre power additions, the ratios are substantially identical. The values of maximum cylinder are as follows:

C_{max} =1.75<A_{nom} =2.00 diopters
C_{max} =2.65<A_{nom} =3.00 dioptres

The principal length of progression in such a lens design is advantageously less than 16 mm. It is 12.4 mm for the lens of lower addition than one dioptre, and has substantially the same value for lenses of power addition 2 and 3 dioptres. The principle length of progression can preferably fall within ranges that have about 15 mm, about 14 mm, or about 13 mm as an upper limit. The lower limit for such ranges can be, for example, about 12 mm, about 11 mm, or about 10 mm. Most preferably, the principle length of progression is about 12 mm, i.e., in the range of about 12 to 13 mm.

a)



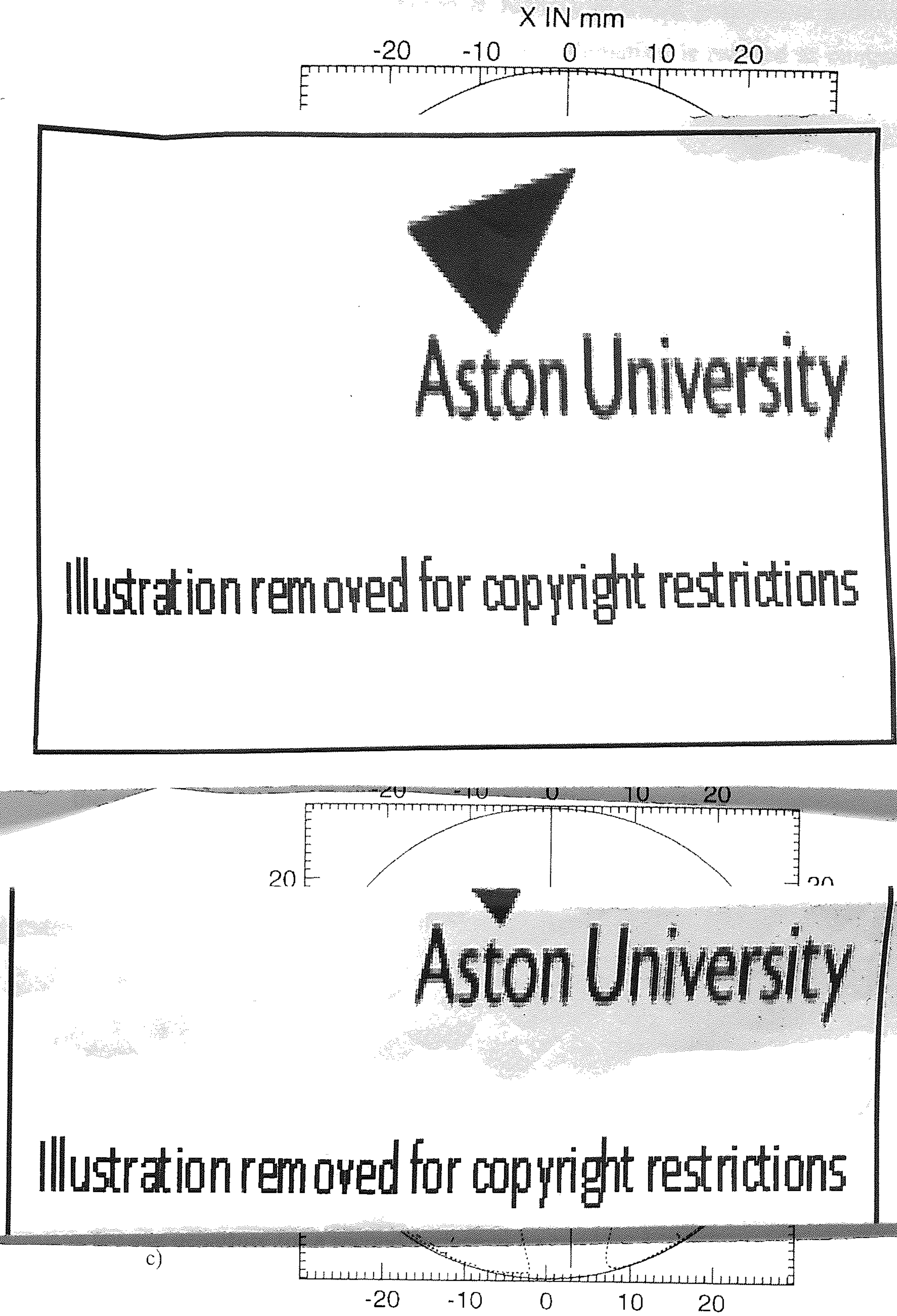


Figure AI.78. *Baudart, et al. multifocal ophthalmic lens. a) Shows graphically variation in power along the meridian of a lens with 1 .00 Add. b) Is a front view of the lens in Fig. a), showing the main meridian of progression and lines indicating the level of mean sphere. c) Is a front view of the lens in Fig. a), showing the main meridian of progression and lines indicating cylinder level. (From Baudart, 2000)*

Menezes, et al. (2000) for Johnson & Johnson provided progressive addition lens designs and lenses in which unwanted lens astigmatism is reduced as compared to previous art conventional progressive addition lenses.

In such an invention, combining the designs of at least two progressive surfaces forms a composite progressive addition surface. Each of the at least two progressive surface designs has a maximum, localized unwanted astigmatism area or areas that are at different locations than those of the surface or surfaces with which it will be combined. By "maximum, localized unwanted astigmatism" is meant the highest, measurable level of astigmatism in an area of unwanted astigmatism on a lens surface. When the designs of the at least two progressive surfaces are combined to form the composite surface design, the areas of maximum, localized unwanted astigmatism are misaligned. Because of this, the maximum, localized unwanted astigmatism of the composite surface is less than that of the sum of the contribution of the surfaces if the areas were aligned.

The misalignment is such that no area of maximum, localized unwanted astigmatism of a surface substantially coincides with that of the other surface or surfaces when the surfaces' designs combine to form a composite surface design.

More specifically in such a lens, following designing and optimizing of each surface, the sag values of the surfaces were summed to obtain the composite surface design, the summation performed according to the following equation:

$$\mathbf{Z(x,y)=aZ'(x,y)+bZ''(x,y)+cZ'''(x,y)+\ (I)}$$

where Z is the composite surface sag value departure from a base curvature at point (x, y), Z' is the sag departure for a first surface to be combined at point (x, y) and Z" is the sag departure for a second surface to be combined at point (x, y), and so forth, and a, b, c are coefficients used to multiply each sag table. Each of the coefficients may be of a value between about -10 and about +10, preferably between about -5 to about +5, more preferably between about -2 and about +2. The coefficients may be chosen so as to convert the coefficient of highest value to about + or -1, the other coefficients being scaled appropriately to be less than that value. The summation of the two surface designs used must be performed so that no unprescribed prism is induced into the composite surface

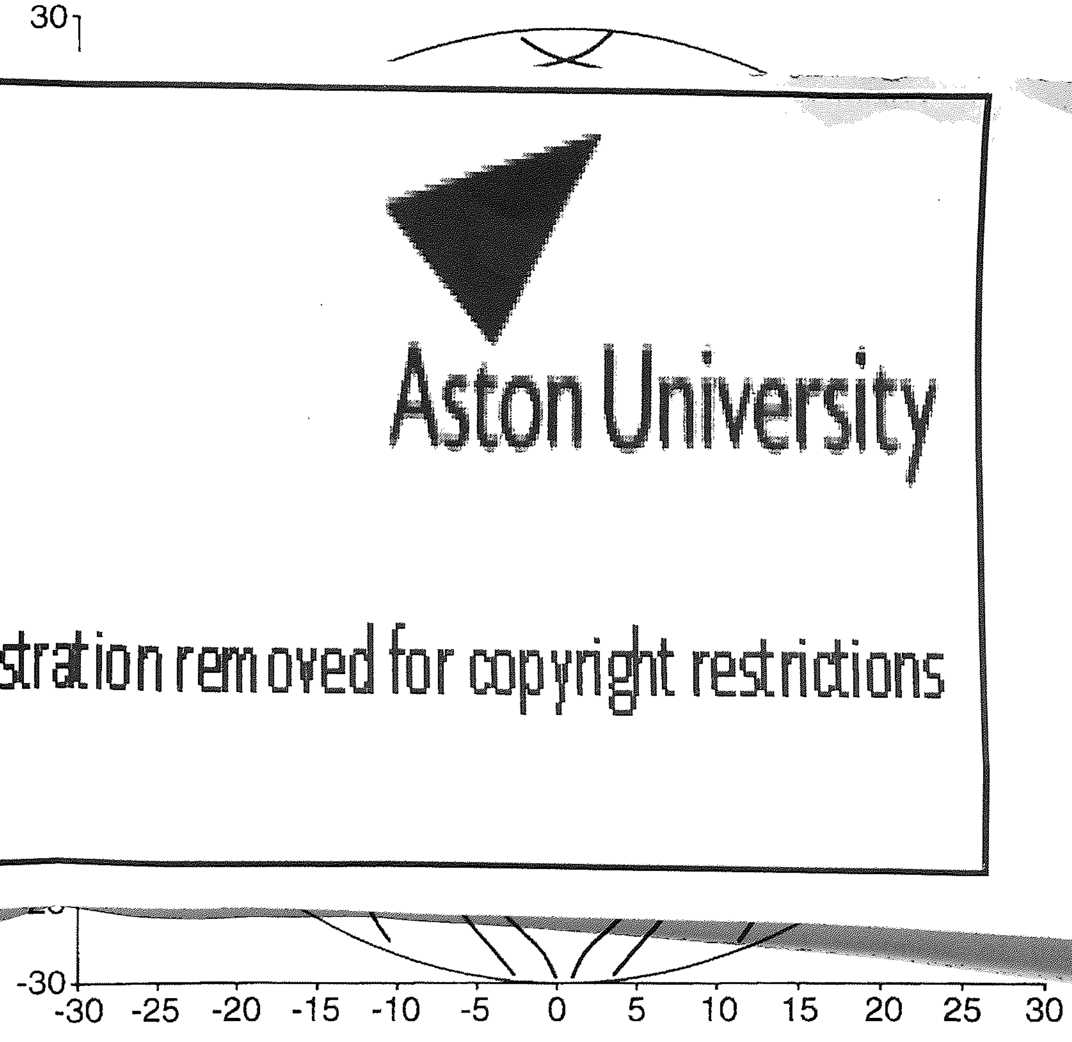


Figure AI.79. *Menezes, et al. progressive addition lens. This is a cylinder map of a composite surface (From Menezes, 2000)*

Menezes, et al. (2000), for Johnson & Johnson again, proposed a better type of progressive lens than the previously mentioned. The reduction of unwanted astigmatism may be constructed by combining progressive addition and regressive surfaces. A regressive surface also has areas of unwanted astigmatism; the magnitude and axis of the regressive surface astigmatism are determined by the same factors that are determinative for the progressive surface astigmatism. However, the magnitude of the regressive surface astigmatism will be opposite in sign to that of the progressive surface astigmatism.

Thus, combining a progressive surface with an area of unwanted astigmatism with a regressive surface with a comparably located area of unwanted astigmatism reduces the total unwanted astigmatism for that area of the lens.

Each surface has a dioptric add power and the total dioptric add power, or add power, of the lens is the sum of the dioptric adds powers of the progressive addition and regressive surfaces. In the lens of the invention, the progressive addition surfaces are of a soft design and the regressive surfaces are of a hard design. The dioptric add power of the progressive addition and regressive surfaces are selected based on a number of factors. For example, the powers are selected based on the total dioptric add power desired for the lens as well as the unwanted astigmatism associated with a given dioptric add power. Additionally, consideration is given to the minimum channel width desired for the lens because the channel width of the lens will diminish as the dioptric add power increases. Yet another consideration is the ability to produce a cosmetically appealing lens or a lens the thickness and base curvatures of which are acceptable to the wearer.

Winthrop (2000) for Sola produced a progressive ophthalmic lens design for use in eyeglass frames having a vertical ("B") dimension <36 mm. The lens features a short (nominally 13-14.5 mm) progressive corridor and a novel treatment of the progressive optics that compensates for the distortion effects, i.e., astigmatism, that would otherwise result from the compression of the optics into a smaller than usual area. The lens has a small amount of the astigmatic aberration, extended into the peripheral zones of the distance portion above the distance fitting centre, with 0.50 D isocurves of surface astigmatism forming an included angle of about 110°, Also the lens is defined by a circle of 30 mm diameter cantered 2 mm vertically below the distance fitting centre in which the maximum value of unwanted astigmatism did not exceed the add value of the lens plus 0.25 D.

A quantitative characterization of the distribution of surface astigmatism, A(x,y), in such a lens can be expressed in terms of the magnitude, v., of the gradient of the surface astigmatism evaluated along specific arcs of the 30 mm circle superimposed on the lens surface, where

$$v = |\nabla A|$$

∇ being the two-dimensional gradient operator, i.e.,

$$\nabla = \mathbf{i}\frac{\partial}{\partial \mathbf{x}} + \mathbf{j}\frac{\partial}{\partial \mathbf{y}}$$

where i is the unit vector in the x direction and j is the unit vector in the y direction. From the law of Minkwitz it is known that the width of a short progressive corridor (generally understood to be the distance between 0.50 D astigmatism lines or between 1.0 D astigmatism lines on opposite sides of the corridor) is necessarily narrower than that of a long corridor. Significantly, this fact has no direct bearing on the overall comfort of the lens of this invention. Overall comfort is determined not locally by corridor width but by the gradients and magnitude of the unwanted astigmatism. A generally soft distribution of astigmatism is experienced as visually more comfortable than a hard distribution. This type of lens design is most suitable for small frames

Figure AI.80. *Winthrop's short-corridor progressive lens. a) Show the surface mean power and astigmatism distributions, respectively, of a 2.00 D add lens of such a lens. The corridor length is 13 mm. (From Winthrop, 2000)*

Baude, et al. (2000) for Essilor proposes a multifocal ophthalmic lens in which the power profile (P) in dioptres of the lens as a function of the height (h) in mm above the axis of the lens and the addition (Add) corresponding to the degree of presbyopia of the wearer is defined by an equation of the form:

$$\mathbf{P(h)=f(P_{VL}, Add, h)+C(Add, P_{VL})h^2 +B(Add, P_{VL})}$$

in which P_{VL} is the power in dioptres required for far vision, f is a function of evolution between the near vision and far vision powers, $C(Add, P_{VL})$ is a spherical aberration correction coefficient depending on the addition and on the far vision power and $B(Add, P_{VL})$ is a power correction coefficient depending on the spherical aberration coefficient.

Menezes, et al (2000) for Innotech, Inc this time proposed an improved progressive lens, very similar to that of patent *US 6139148*.

The invention provides progressive addition lenses, as well as methods for their design and production, in which the maximum, localized unwanted astigmatism that is associated with a given dioptric add power is reduced. Additionally, the distance width, or width about the optical centre of the lens that is free of about 0.50 dioptres or more of unwanted astigmatism, and minimum channel width of the lens is suitable for use by the lens wearer.

The lens of the invention exhibits less maximum, localized unwanted astigmatism and a wider channel than would be expected by producing a lens with the same dioptric add power using only a single progressive addition surface. Further, the use of more than one progressive addition surface ensures that the distance dioptric power and the total dioptric add power needed to correct the wearer's vision is uncompromised. The progressive surfaces' dioptric add power areas are misaligned with respect to one another, the resultant total maximum, localized unwanted astigmatism of the lens is less than the sum of the maximum, localized unwanted astigmatism contributed by the individual dioptric add powers of each progressive addition surface.

The amount of misalignment, or the vertical shift, lateral shift or rotation of optical centres, is an amount sufficient to prevent substantial superposition, or coincidence, of the maximum, localized unwanted astigmatism areas of the progressive addition surfaces. More specifically, the misalignment leads to a mismatch of the direction of the astigmatic vectors associated with one surface relative to the corresponding astigmatic vectors of the other surface resulting in the total maximum, localized unwanted astigmatism for the final lens being less than that if the vectors were aligned. The lateral or vertical shift is about 2.0 mm to about 4.0 mm. Rotational shifts may be about 10 to about 20 degrees.

The maximum, localized unwanted astigmatism value of 1.90 D for this lens is shown in the next Table AI.7 and is significantly lower than the 2.20 D that is found in a conventional PAL of the same near dioptric power.

Table AI.7

A	Add power front (D)	Add power back (D)	Add power total (D)	Vertical shift (mm)	Max Astigm (D)	Max Astigm /Add ratio
Prior art	2,00	0,00	2,00	0,00	2,20	1,10
1	1,00	1,05	2,00	4,00	1,90	0,90
2	1,05	1,05	2,10	8,00	1,90	0,90

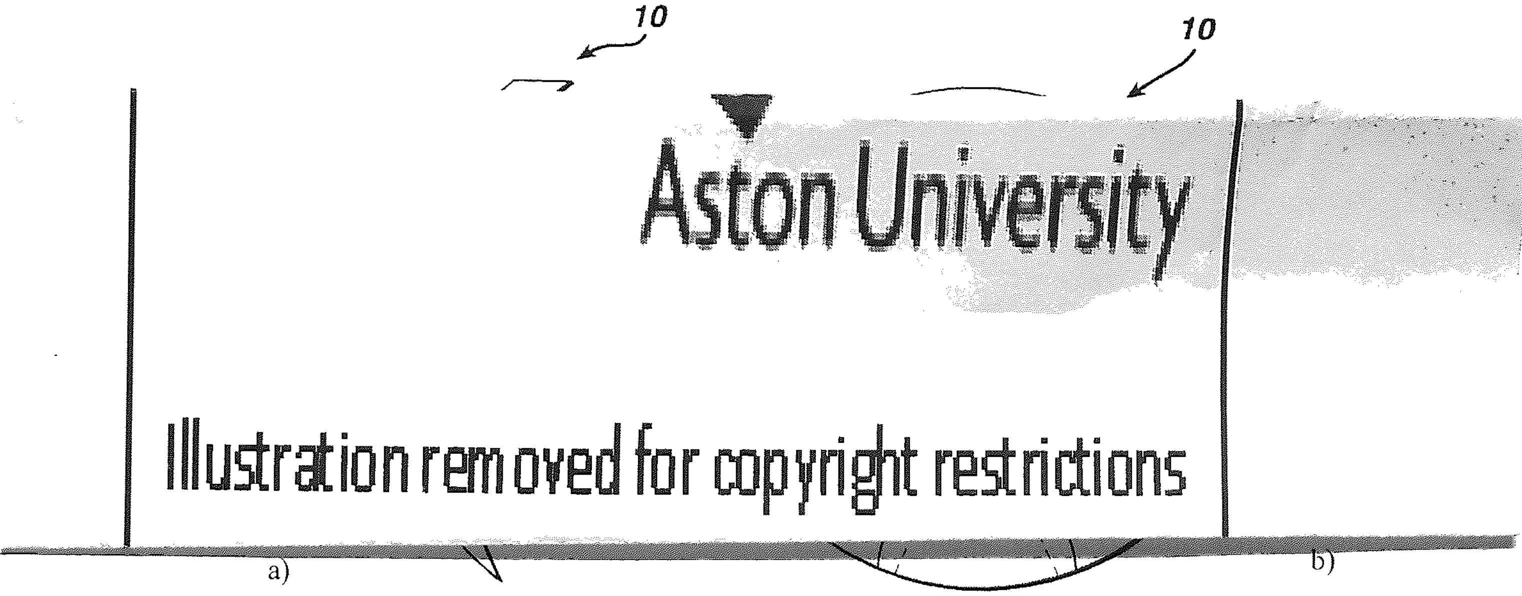


Figure AI.81. *Menezes, et al progressive addition lens. a) Is a side view of a lens of the invention. b) Is an astigmatism map of the lens. (From Menezes, 2000)*

Kris, et al (2000) for Sola, presented a progressive ophthalmic lens and in particular an ophthalmic progressive lens exhibiting improved optical performance in the distance and intermediate viewing regions. Such spectacles lenses were designed specifically for distance and intermediate vision and providing improved flexibility for the wearer, with an improved angular range of visual fields and greater tolerance to fitting variability.

The lenses were designed with reduced sensitivity to horizontal fitting errors (such as errors in pupillary distance measurement of the wearer) and vertical fitting height errors related to frame and face conformation measurement errors. This would make such lenses more similar in ease of fitting to single vision-reading lenses. The progression length is preferably approximately 10 mm. The intermediate vision distance varies from 2.00 to 1.00 depending on the need of the wearer.

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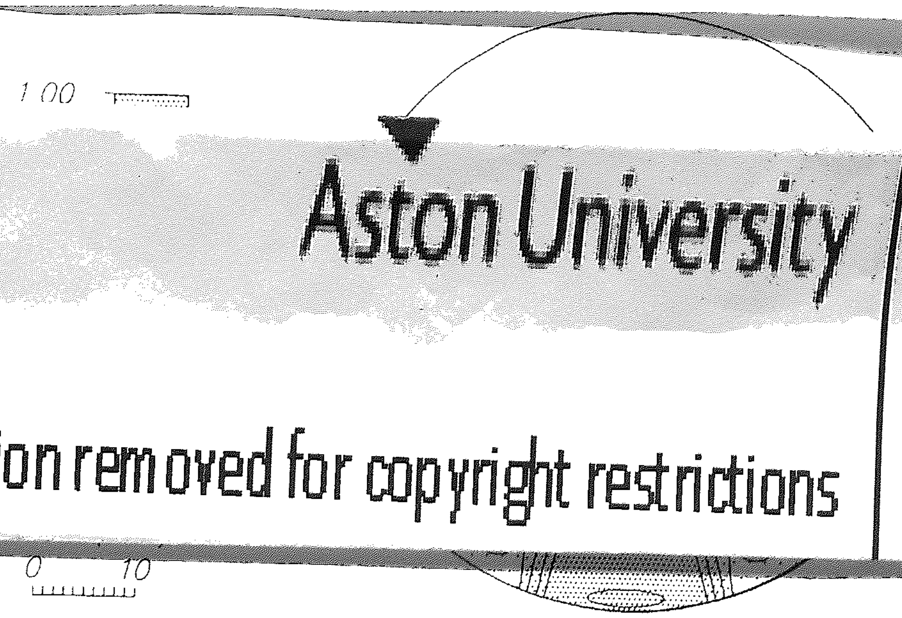

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Figure AI.82. *Illustrates the surface astigmatism contours, mean surface power contours of a progressive lens element having a 5.00 D base are and 1.00 D addition power, indented for distance and intermediate vision (From Kris, 2000)*

Altheimer, et al (2001) for Rodenstock provided a progressive ophthalmic lens, which could have negative power, in the distant vision reference point and which has a relatively wide near vision zone, which is at least 25% wider than the near vision zone in known progressive ophthalmic lenses.

François, et al. (2001) for Essilor proposes a lens design which improves the behaviour of the lenses in peripheral vision, for lenses which already have good foveal monocular or binocular vision on at least the principal line of sight or principal meridian. Such a lens ensures correct dynamic vision, and appropriate fusion of the images provided by the eyes outside of the static vision fields.

Francois takes into account, a binocularity parameter, which is defined for a given fixation point. This fixation point may be any point in the object space, since its only function is to allow the pupils to rest in a fixed position. For one point in the object space, the binocularity parameter is defined as the difference in mean sphere on the aspherical surfaces of the lenses between points of the surfaces corresponding to rays originating from both pupil centres and directed towards said point. Over the aspherical surface lens, for the whole visual field, this difference should be as small as possible.

An upper limit or maximum value for this difference is given; when the difference lies below this limit for all points of the aspherical surface of the lens, or for the different peripheral directions, acceptable binocular vision is ensured for the whole field of vision of the lens, and the wearer of the spectacle lenses benefits from correct dynamic vision.

This binocularity parameter is defined, for a point (M) in the object space as the relative difference ΔS of the mean sphere for the points (M_D, M_G) of the aspherical surface of the right and left lenses through which the wearer sees said point (M). This relative difference ΔS is defined by the formula

$$\Delta S = 100 \, x \quad S_D - S_G \, / \, (S_D + S_G)/2$$

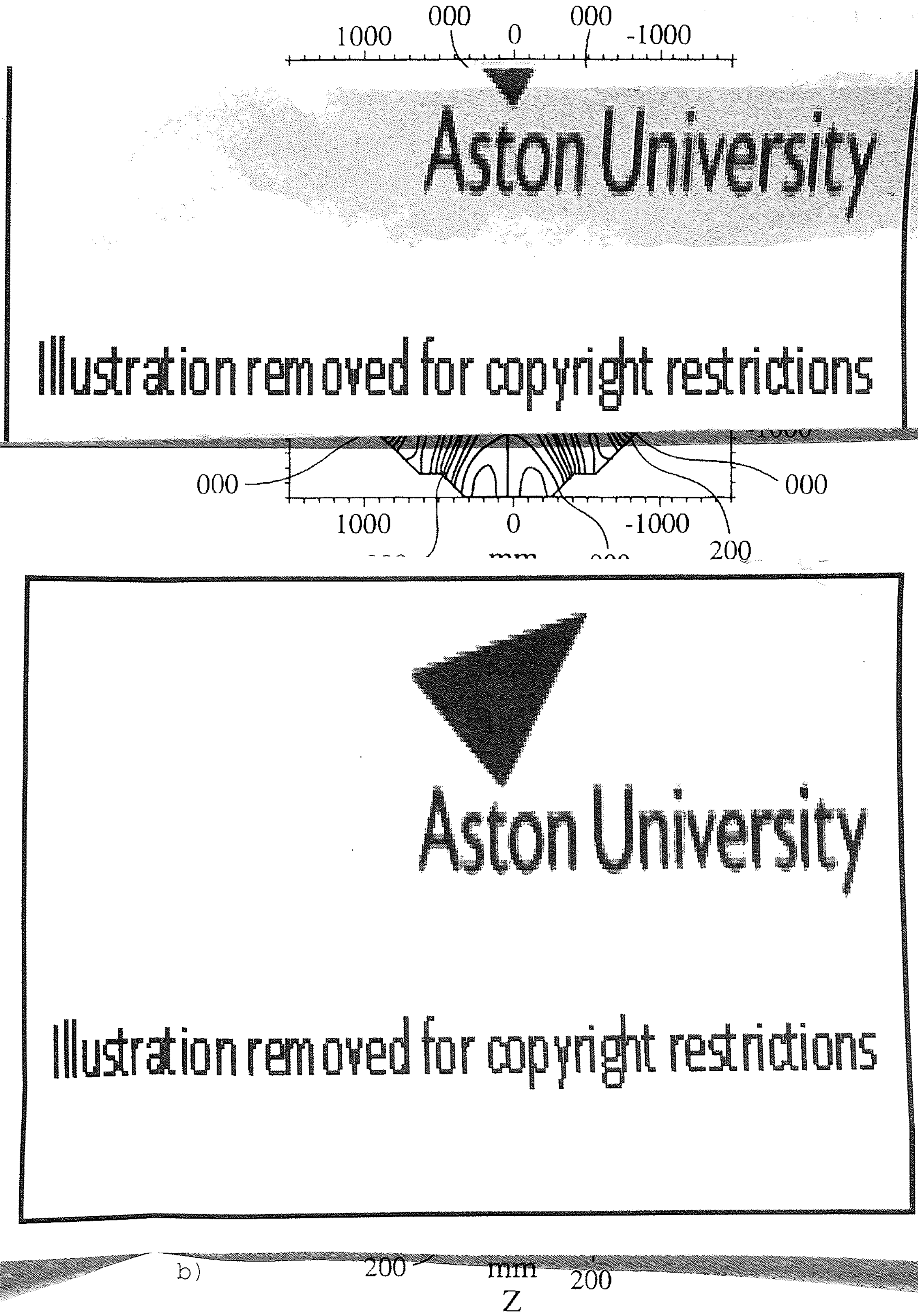


Figure AI.83 *a) Shows the relative values of the mean sphere difference, for a lens of prior art having an addition of one diopter. The peak to valley value of the binocularity parameter ΔS, that is the difference between the highest and the lowest value of ΔS over the lens is 6.49. b) Shows the relative values of the mean sphere difference for the proposed lens having an addition of one diopter. The peak to valley value amounts to 3.01. (From Francois 2001)*

Menezes (2001) for Johnson & Johnson *provided* a lens design where the channel power profile was made to suit the wearer's requirements. This is made possible by using two surfaces, each having a channel power profile. The channel power profiles may be displaced in reference to each other. By displaced is meant that major reference point of one channel is displaced downwardly with respect to that of the other channel. In general, the channel power profile, P(x,y), of a progressive lens may be calculated as a vector sum of the profiles of each surface of the lens. For a lens with two progressive surfaces, S' and S", which surfaces have channel power profiles P'(x,y) and P"(x,y), respectively, the power profile for the lens may be calculated according to the following equation:

$$P(x,y)=P'(x,y)+P''(x-dx,y-dy)$$

wherein dx and dy are the x and y components of the displacement of the fitting point of surface S" with respect to surface S'. S' is a convex progressive surface and S" a concave progressive surface. Surface S" may be displaced vertically downwards relative to S' by a distance dy. If L' is the channel length of surface S', L" is the channel length of the surface S", and L">L', then the channel length L of the lens formed by combining surfaces S' and S" is calculated as

$$L=L''+dy$$

Both the channel power profiles of the two surfaces and displacement distances may be selected so that the channel power profile is customize for a particular wearer. The displacement of the channel power profiles will also misalign the areas of maximum unwanted astigmatism of the surfaces and the overall maximum astigmatism of the lens will be lower than the sum of the individual surfaces. The displacement may be preferably about 2 mm to about 7 mm.

Such a method requires measuring the wearer's eye path and refractive power while the wearer is viewing an object at a distance, an intermediate, and a near position in order to provide a lens with a channel power profile based on the lens wearer's eye path and refractive requirement. This requires an expertise dispenser for such lenses.

The eye path measurements for a lens wearer should be conducted separately for each eye because each of the wearer's eyes usually has a unique eye path. With such a method a variety of power profiles for one lens wearer can be provided, each suited to a specific task to be carried out by the wearer. For example, displacement may increase the channel profile length so that a lens for intermediate distance tasks is provided. Alternatively, the profile may be shortened to provide an elongated near vision zone for reading.

Baudart, et al. (2001) on behalf of Essilor provided a set of progressive multifocal ophthalmic lenses, taken into account the optical characteristics of the lenses, and particularly wearer power and oblique astigmatism, in worn conditions. For this purpose, the use of an ergorama associating with each sight direction in worn conditions, a target object point, and a given power is necessary to provide an optimized design. This ergorama supplies a power target for a definition by optimisation of the lenses, and is used in a radii-plotting programme for calculating the optical characteristics during optimisation. The set of lenses has substantially identical optical performances for a given addition, whatever the power of the far vision reference point.

Menezes (2003) again for Johnson & Johnson provided lenses, as well as methods for their design and production, in which prism power was introduced. This added prism power overcomes, in whole or in part, the adverse image quality effect of the lens un-prescribed prism power.

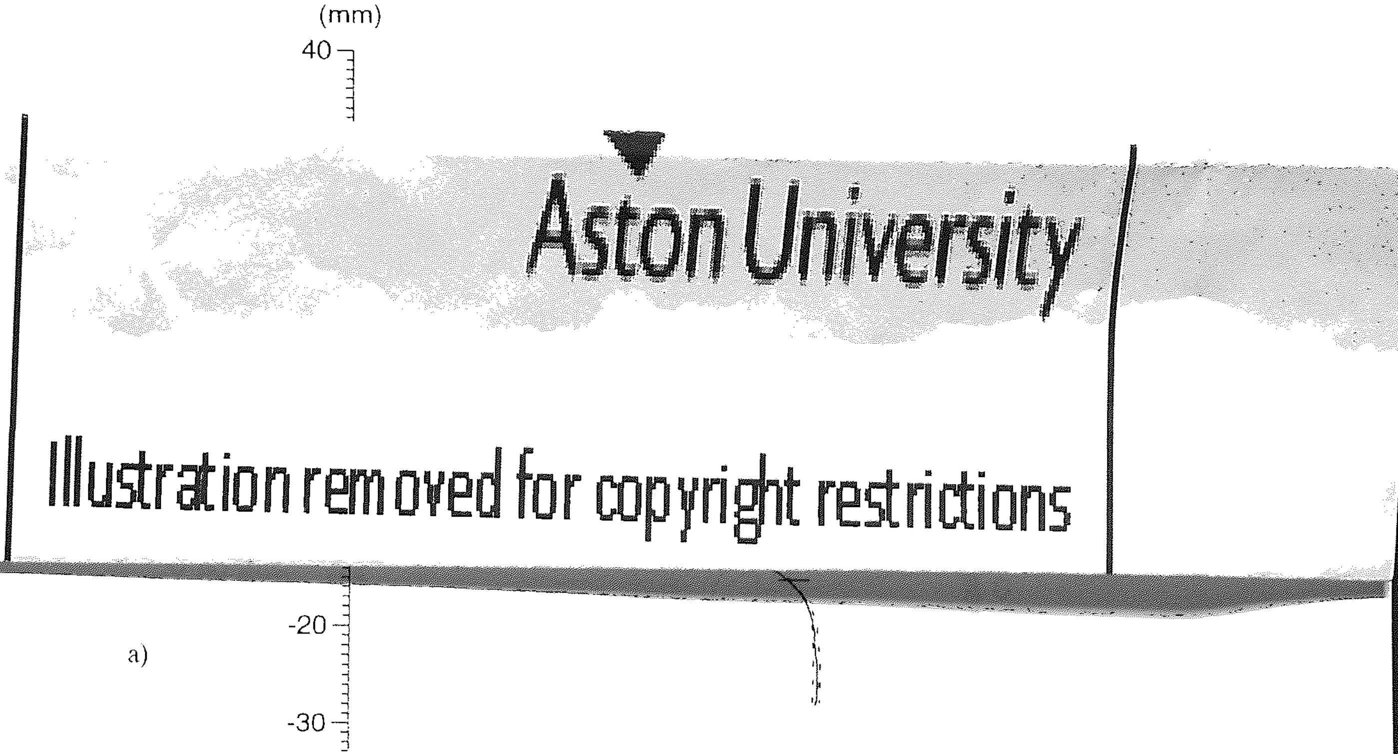
The progressive addition lens comprised a vertical prism having a power and a base, added to substantially the whole lens, where the added vertical prism base was opposite in direction to the near vision zone vertical prism base and equal to about 0.25 percent of the add power.

In Figure (AI.84) It is seen a lens 50 in which there is introduction of a uniform magnitude of base down prism at an interface of two surfaces 54 and 55 of the lens, one surface being made from a material of a refractive index of 1.60 and the other of 1.50. The convex surface 54 of the lens has a distance zone curvature of 6.00 dioptres and near zone curvature of 7.00 dioptres. The concave surface 55 distance zone has a curvature of 6.00 dioptres and a near zone curvature of 5.00 dioptres. The lens' distance power is 0.00 dioptres and the add power is 2.00 dioptres. The curvature of the interface 56 is 6.00 dioptres and is tilted, relative to the convex surface by 6 degrees (D) to produce base down prism (P) over the whole lens. Solid lines 51 and 52 show the ray traces for the distance and near lines of sight, respectively through the lens and dotted line 53 depicts the ray trace absent the added prism.

Figure AI.84. *shows a progressive addition lens produced with convex surface tilted to produce base down prism. The lens was formed after casting the progressive addition surface onto an optical preform. Vertical prism was added to the lenses by tilting the glass mold used to cast the progressive addition surface some degrees difference in relation to the preform about the preform's x-axis. (From Menezes 2003)*

Chauveau, et al. (6,540,354, 2003) for Essilor introduced a progressive addition lens which provides wearers with improved peripheral vision while still ensuring foveal vision was good and consequently ensuring ease of adaptation of wearers to their lenses. The lens presented rapid progression of mean sphere, ensuring the presence of a large near vision region. It also provided balanced distribution of isosphere and isocylinder lines. The sphere value varied in a monotonous fashion as a function of angle on a 20 mm radius circle cantered on a geometric centre of the lens at both sides of said meridian and in which the far vision region was delimited in an upper portion by lines formed of points for which cylinder was equal to half power addition.

The principle length of progression ranged between 12 to 13 mm. The lens was more dedicated to near vision and intermediate vision.



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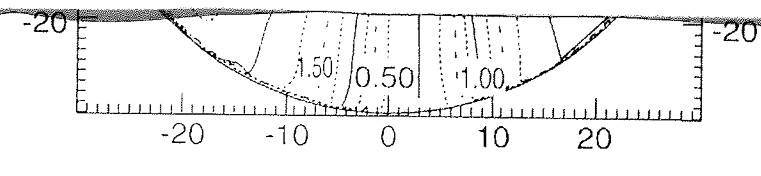

Figure AI.85. *Is a front view of the lens showing a) the main meridian of progression for addition 3.00.the level of mean sphere b) the level of mean sphere the level of astigmatism presented c) the level of astigmatism presented. (From Chauveau, 2003)*

Continuing the work for Essilor *Ahsbahs, et al. (2003)* provided a progressive lens with a small progression length, and a near vision region, which is high on the lens. It is suitable for frames of small size, and is less tiring in extended use. In an example given, the value of L (progression corridor) is 7.64 mm, that means that the region of near vision, which starts substantially at the height at which 85% of the addition or of the ratio S_{max} -S_{min} is reached, is very nearly 5 mm under the geometric centre of the lens. This position corresponds to the position of the area of near vision in the bifocal lenses of the prior art; in this way, as explained above, easy adaptation by wearers of bifocal lenses to the progressive lenses according to the invention is ensured. In fact, no change in posture is needed to go from bifocal lenses to a lens of the invention.

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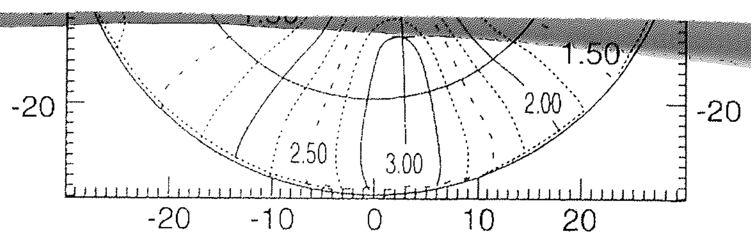

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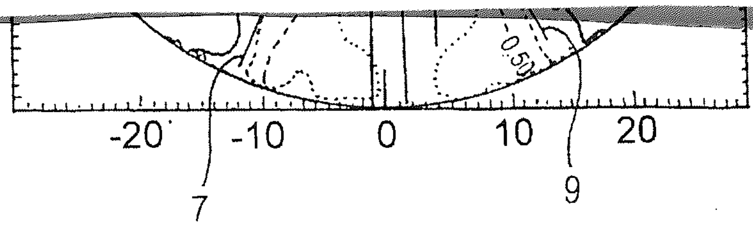


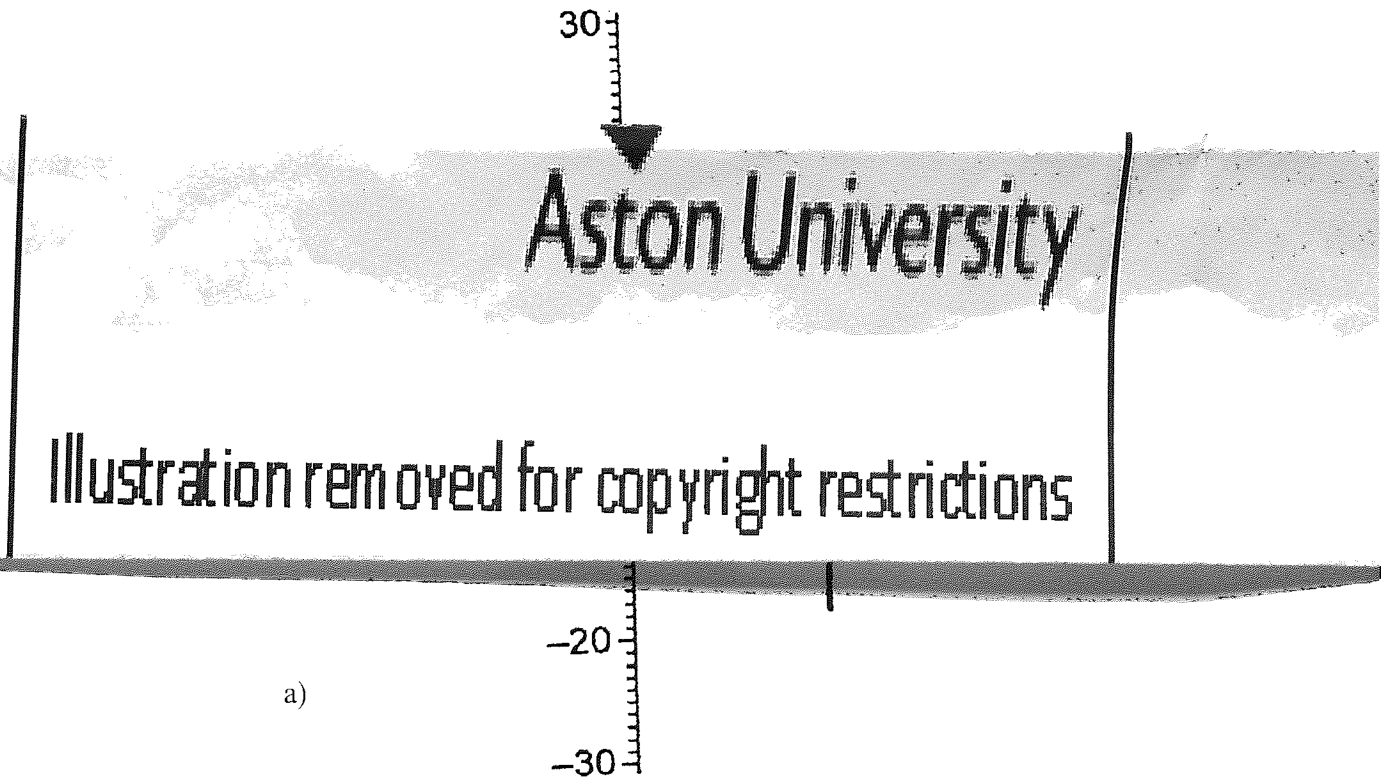
Figure AI.86. a*) Is a graph of mean sphere along the meridian of a lens 1.50 D addition b) Is the mean sphere map of the lens and c) Is the cylinder map. (From Ahsbahs, 2003)*

Yamakaji, et al. (2003) for Hoya proposed a lens design which achieves a higher performance by designing the spectacle lens using a value determined for each individual spectacles wearer, such as a value of distance VR from a reference point on the back surface of a spectacle lens to the centre of rotation of the eye when the spectacle lenses is worn, which is one of the necessary data in the lens design. The lens then is manufactured based on specific design specifications comprising the prescription value, spectacle frame information, and data related to the VR value of a spectacles wearer, layout information, and process specification information.

Welk, et al. (2003) for Rodenstock proposed a lens design based on the object that the lens will not only have a large distance portion and a large near portion, but also that swaying sensations are avoided, particularly upon rotating movements of glance.

According to the objective of the design no surface values were taken into account, but only parameters which relate to the wearing position, namely the deviation from a given astigmatism (which is 0 dpt for an astigmatism-free eye, or has the magnitude and cylinder axis of cylinder prescription values).

Ahsbahs, et al. (2004) for Essilor again proposed a new solution to provide a lens of generalized optical design, suited to all situations. It provides in particular a lens able to be mounted in small size frames < 35mm, without the near vision region getting reduced. It also improves wearer comfort with prolonged use of the near vision or intermediate vision regions. It makes it easier for younger presbyopic wearers and former wearers of bifocal lenses to adapt to progressive lenses. More generally, the invention is applicable to any lens having a rapid variation in power. The lens progression corridor is less than 12.5 mm.



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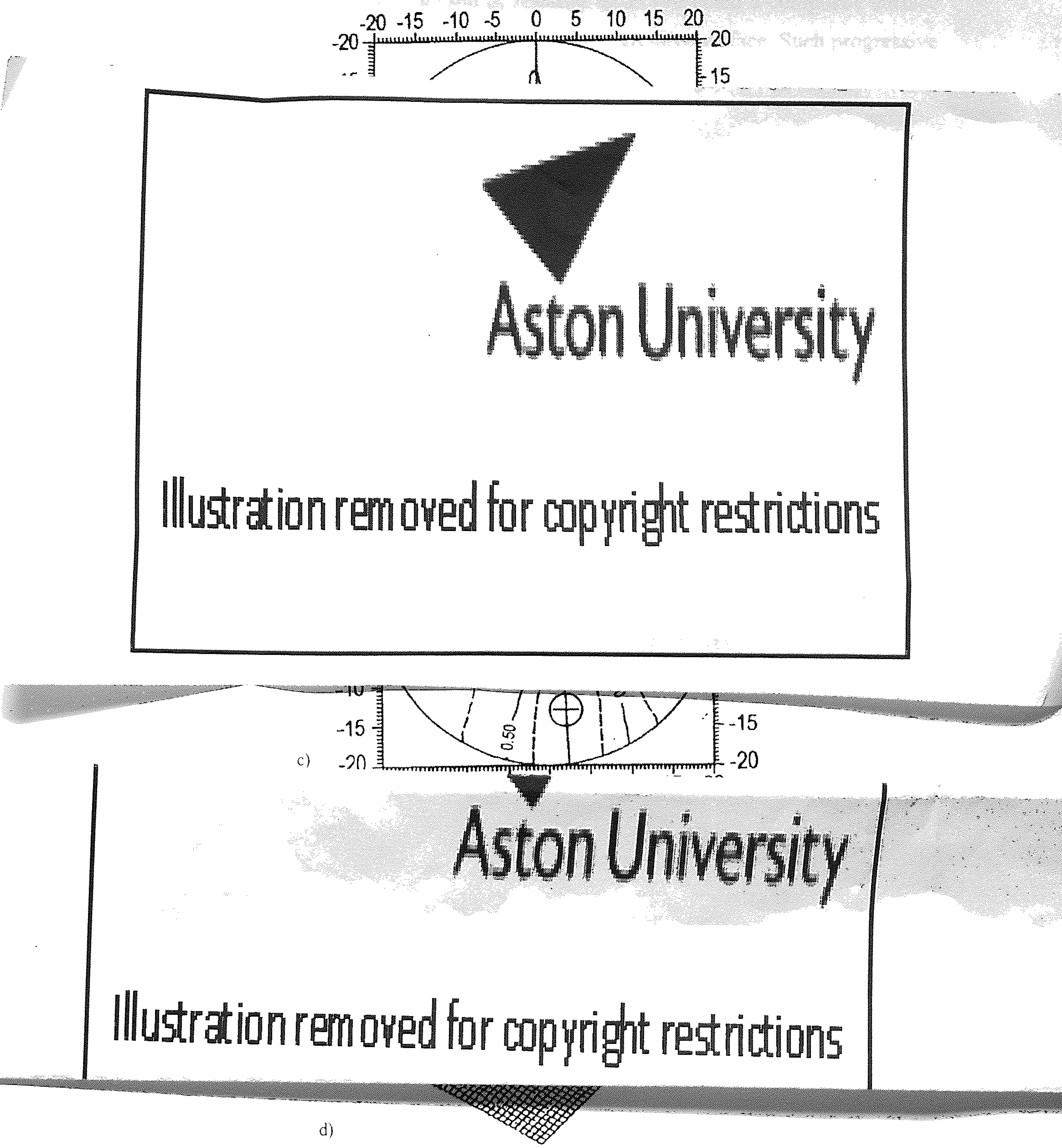

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Figure AI.87. *a) The main meridian of progression for addition 1.00. b) The level of mean sphere c) the level of astigmatism presented d) a 3-dimensional representation of the product (slope of sphere times cylinder). (From Ahsbahs, 2004)*

Menezes (2004)(2005) for Johnson & Johnson again presented a composite surface by combining the designs of a progressive and a regressive surface. Such progressive lenses presented reduced unwanted astigmatism The method for designing such a progressive addition surface consisted essentially of: a.) designing a progressive surface having at least one first area of unwanted astigmatism; b.) designing a regressive surface having at least one second area of unwanted astigmatism; and c.) combining the progressive surface and regressive surface designs to form a composite progressive surface design, where the first and second areas of unwanted astigmatism are aligned.

The terminology used such as "regressive surface" is meant a continuous, aspheric surface having zones for distance and near viewing or vision, and a zone of decreasing dioptric power connecting the distance and near zones. If the regressive surface was the convex surface of the lens, the distance vision zone curvature will be greater than that of the near zone and if the regressive surface was the lens' concave surface, the distance curvature will be less than that of the near zone.

The areas of unwanted astigmatism were disposed so that there is partial or substantially total superposition or coincidence when the surfaces are combined to form the composite surface.

The composite surface produced by combining a soft design with a hard one. The soft lens design progressive addition surface was used having a base curvature of 5.23 dioptres for the distance zone. The add power was 1.79 dioptres with a channel length of 13.3 mm. Then a hard design regressive surface was produced with a base curvature of 5.22 dioptres for the distance zone. The add power was -0.53 dioptre, and the channel length was 10.2 mm.

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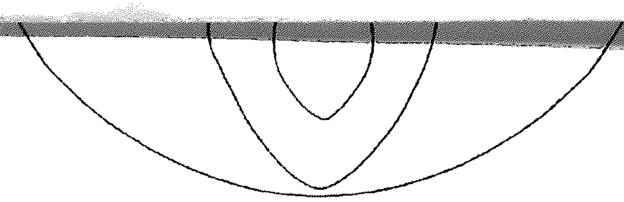


b)

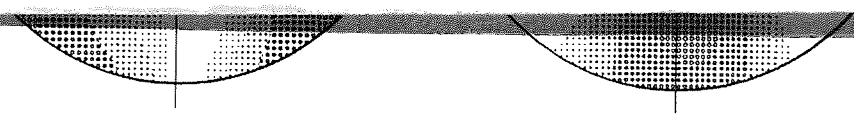
Figure AI.88. *The composite surface had a base curvature of 5.23 dioptres and an add power of 1.28 dioptres. The magnitude of this astigmatism maximum was 0.87 dioptres and the channel length is 13.0 mm. a) and b) show the cylinder and sphere contour map of such lens. (From Menezes 2004)*

Kitani (2004) for Hoya proposed different lens design depending on the prescription of the wearer. For a lens with a (+) prescription at the distance portion having positive refractive power, the design incorporated correction such that *transmission astigmatism* at each point on the principal sight line is minimized, whereas for a lens with a (-) prescription at the distance portion having negative refractive power, it incorporated correction such that *transmission average refractive power error* at each point on the principal sight line is minimized.

As regards the near portion, minimizing transmission astigmatism or minimizing transmission average refractive power error, this is regardless of whether the lens is for correcting hyperopia or for correcting myopia. On the one hand, when someone tries to minimize transmission astigmatism in the near portion at a progressive power lens with a shallow base curve, the transmission average refractive power error (curvature of field) in the near portion will be (-) for one with positive distance-vision power and conversely (+) for a negative one.

In other words, this means that for one with positive distance-vision power, addition will act weakly, while for a negative one it will act strongly. Here, where addition is weak, the associated distortion will also be stronger than necessary. Accordingly, the choice exists to improve transmission average refractive power error in the distance portion and near portion while leaving transmission astigmatism in the reference points of the distance portion and near portion completely uncorrected. Also the proposed design style provides a progressive power lens with superior wear comfort, even where a shallow base curve is employed in order to make the lens lighter and thinner, which is desirable in the terms of weight and aesthetic design.

In Figure AI.89, transmission meridional power for distance vision, intermediate vision, and near vision is the reciprocal when the respective distances from symbols Kf, Km, and Kn to symbols Tf, Tm, and Tn are expressed in meter units. Transmission sagittal power for distance vision, intermediate vision, and near vision is the reciprocal when the respective distances from symbols Kf, Km, and Kn to symbols Sf, Sm, and Sn are expressed in meter units. Transmission astigmatism for distance vision, intermediate vision, and near vision is the difference between each transmission meridional power and transmission sagittal power; reference power for distance vision, intermediate vision, and near vision is the reciprocal when the respective distances from symbols Kf, Km, and Kn to symbols Rf, Rm, and Rn are expressed in meter units. The error of transmission average refractive power for distance vision, intermediate vision, and near vision is the remainder resulting from subtracting each reference power from each transmission meridional power and transmission sagittal power average power.



b)

* EXAMPLE OF COMPLETELY CORRECTED TRANSMISSION ASTIGMATISM

Figure AI.89. *a) Is a diagram illustrating transmission astigmatism and transmission average refractive power error (curvature of field) with spectacle wear b) is a diagram showing transmission astigmatism distribution and transmission average refractive power distribution of the proposed progressive addition lens. (From Kitani 2004)*

Haimerl, et al. (2004) for Rodenstock proposed a lens where a change of binocular imaging properties with horizontal movements of glance is minimized. With such a lens design any lift (difference between a maximum and a minimum value occurring during a movement) of binocular imaging properties when a moving object is being followed, is made smaller than a physiologically predetermined limiting amount.

It has been understood that the binocular properties that are relevant to such an objective are the astigmatic difference, the refraction equilibrium, and the vertical prismatic deviation. These parameters are obtained by computing the principal ray from the centre of rotation of the right eye through a point on the front surface of the right-hand spectacle lens to the object point, and the associated wave front. From the data of this wave front and the prescription for the right eye, the astigmatic deviation and the refraction error are computed. Subsequently the principal ray and the wave front from the object point through the centre of rotation of the left eye are iterated, assuming intersecting visual axes (orthotropy).

Welk, et al. (2004) again for Rodenstock proposed a lens very similar in concept with Haimerl. Here the effort again was to minimize the change of imaging properties with binocular horizontal movements of the gaze.

Menezes (2005) for Johnson & Johnson proposed a different type of progressive addition lens comprising: a.) a distance vision power zone; b.) a near vision power zone comprising an add power; c.) an intermediate vision power zone between the distance and near vision power zones; and d.) a fourth zone located inferior to the near vision power zone, wherein the fourth zone has a constant power that is within about 20-25 to about 75-80% of the add power. The fourth zone is blended continuously with the near zone, having a width of the fourth zone is about 5 to about 25 mm and a length of the fourth zone is about 10 to about 20 mm. The zones are positioned such that the wearer is able to use the lowest portion of the lens to clearly view objects at distances more than about 45 cm from the eye.

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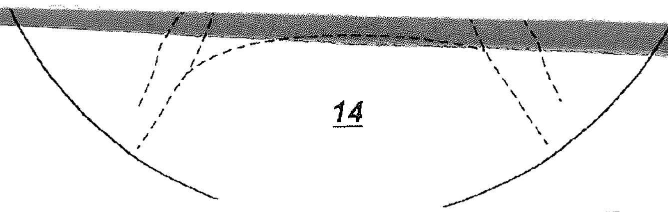

a)

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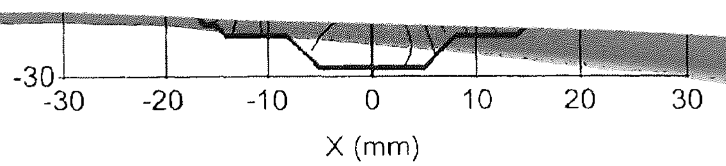

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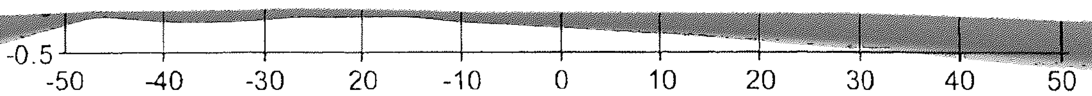


Figure AI.90. *a) Is a plan view of the surface of a lens with the four zones b) is a scanned image of the power contour map of the lens c) is a scanned image of the astigmatic contour map of the lens d) is the channel power profile for the lens (From Menezes 2005)*

Appendix II.

Basic types of interferometers

The most well know types of interferometers are:

Newton Interferometer

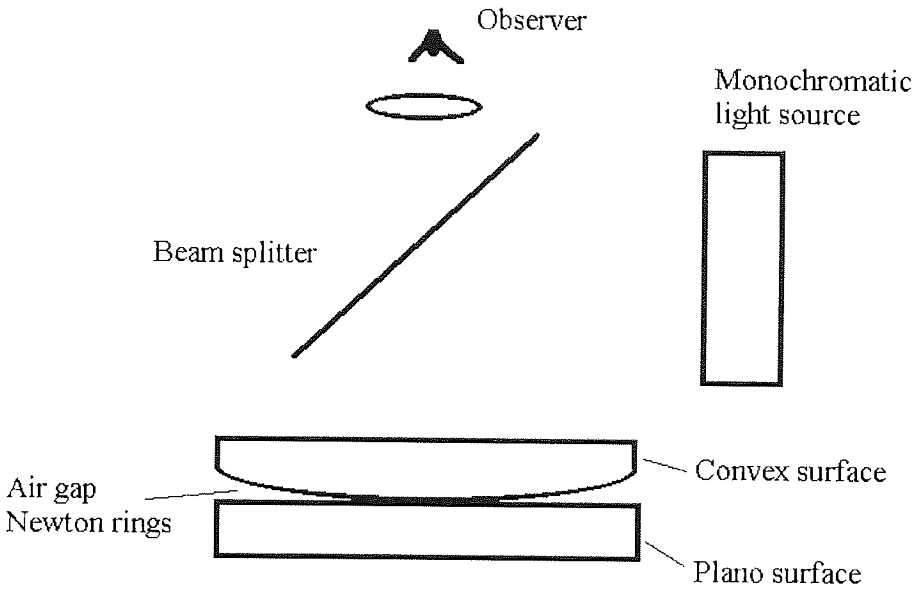


Figure AII.1. *A Newton interferometer. The fringe pattern is localized at the air gap and is observed vertically.*

Figure AII.1. is a schematic representation of the simplest interferometer known as the Newton interferometer where one plane surface (reference surface) and the convex surface of a plano-convex lens are attached making contact at the center apex of the convex surface. These two optical elements are illuminated using monochromatic light, like the light emitting from a sodium vapor lamp or a helium discharge lamp. The beam coming from the source is reflected from the beam splitter, which is 45° from the vertical passing through the two surfaces under contact. By observing Newton's fringes we can determine the sag of the convex surface under test, *(Malacara, 1992)*

$$s = x^2 / 2R$$

s is the sag, x is the distance measured from the center of symmetry of the concentric fringe pattern viewed and R the radius of curvature of the convex surface. The OPD (optical path difference) then is *(Malacara, 1992)*

$$OPD = x^2/R+\lambda/2)$$

From the above we can determine the distance of the *nth* dark fringe from the center of symmetry of the concentric fringe pattern, *Malacara (1972)*

$$x_n = \sqrt{nR\lambda}$$

x_n is the distance from the center of fringes to the nth dark fringe n is the absolute number of the fringe measured (e.g. the 5^{th} n=5, R is the curvature of the tested surface and λ is the wave length of the monochromatic source used).

In order to determine whether the surface tested is convex or concave a pressure is applied at the edge of the two optical elements in contact. If the center of the fringe pattern moves towards the point of applied pressure then the surface is convex while if it moves on the opposite position is concave. The nature of Newton's fringes can determine the type of a surface under test compared to a reference flat as it is seen below Figure AII.2. *(Malacara, 1972)*

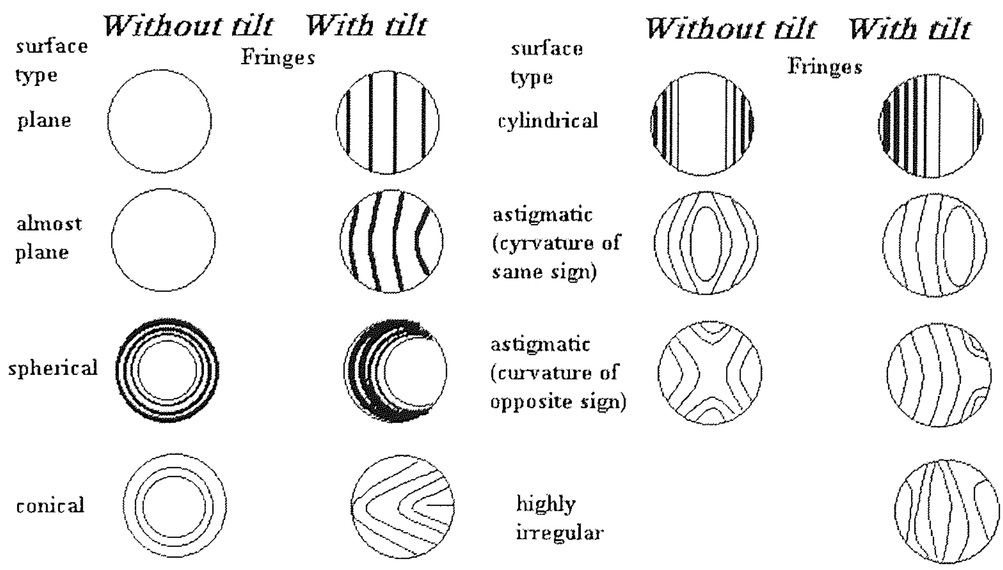


Figure AII.2. *The Newton fringe patterns depending on the surface tested.*

The use of Newton interferometers in optical testing

The Newton interferometer has been used in the past to measure the flatness of glass or opaque surfaces *(Schulz, 1971), (Charman, 1955), (Murty, 1963),* spherical surfaces *(Saunders, 1954)* and aspheric surfaces *(Malacara & Corneo, 1970)*. The last two utilized Newton's fringes in order to determine how the aspheric surface deviates from a known spherical. The method consists of a spherical test plate in contact with the aspheric while the fringes were observed by means of a low power traveling- microscope (x 5). Since the aspheric surface might not have rotational symmetry so several measurements should be taken along different diameters. More recently a Newton interferometer was used to determine the surface parameters for aspheric aphakic lenses, such as radius of curvature at the lens vertex, the asphericity, and astigmatism and the surface quality of the lenses *(Medhat, et al., 1991)*

Michelson interferometer

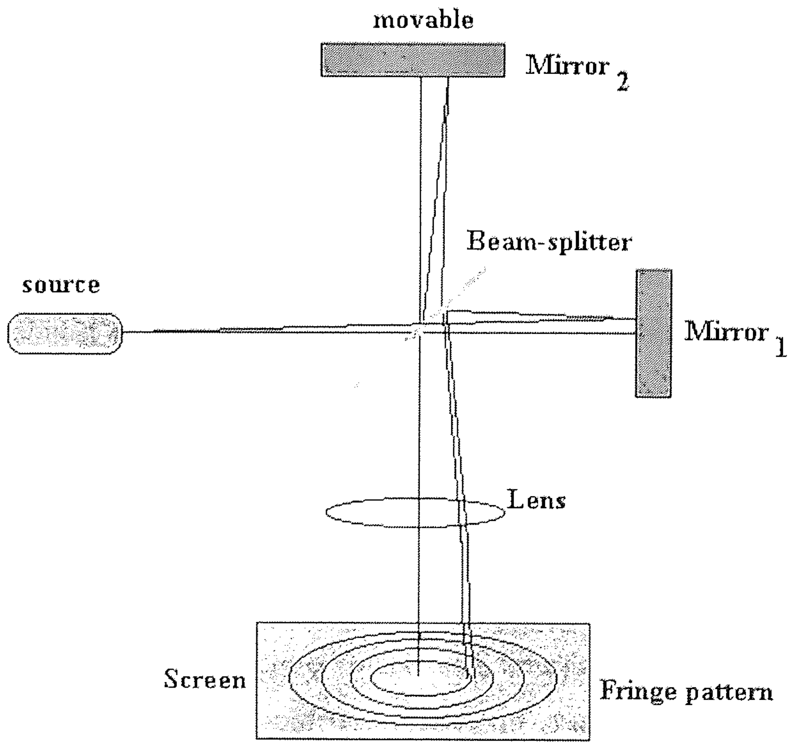


Figure AII.3. *Configuration of the Michelson interferometer*

The arrangement of such an interferometer is shown schematically in Figure AII.3. *Michelson (1906), (1918), (1927),* describes such a device in detail. It consists of two highly polished plane mirrors M_1 (usually fixed) and M_2 (movable) and a beam splitter. The incident wave from a monochromatic light source strikes the beam splitter at 45°. The initial wave is split into two other waves.

In Figure AII.3 part of the initial wave is transmitted to mirror M_1 and part is reflected to mirror M_2. After reflection of the divided wave onto the two mirrors M_1 and M_2 the two components of the initial wave, are recombined at the beam-splitter, where part of the wave is reflected onto the screen, where the fringes are observed and part is transmitted back towards the source producing the initial wave. The move of the movable mirror M_2 is adjusted by screws, which are turned in such a way so that a set of concentric fringes will appear.

The Michelson interferometer as an optical instrument provides results of high precision. It can be used to investigate even very small differences in optical path lengths. The fringe patterns that someone can get from a Michelson interferometer could be either circular or the straight-line type. Circular fringes are produced when the mirrors are in exact adjustment and this type of fringe pattern is the one that is used for measurements. This type of fringes is known as fringes of *equal inclination.* Localized almost straight fringes are seen if the two mirrors are not exactly parallel. This type of fringes is known as fringes of *equal thickness*.

The Michelson interferometer is based on division of amplitude rather than on division of wave front. This means that the two beams, produced after the split of the initial one coming from the source, will travel different optical paths. Then they recombined on the beam splitter plane and interfere forming fringes patterns. Usually this type of interferometer is used in measurements of length or the wavelength of light.

The use of Michelson interferometer in optical testing

A modification of Michelson interferometer utilizing prisms was used to measure flatness, parallelism, angularity, curvature, length and surface quality *(James Tew, 1966)*. *(Murty, 1959)* used Michelson interferometer to simulate the primary aberrations of a lens.

Fizeau interferometer

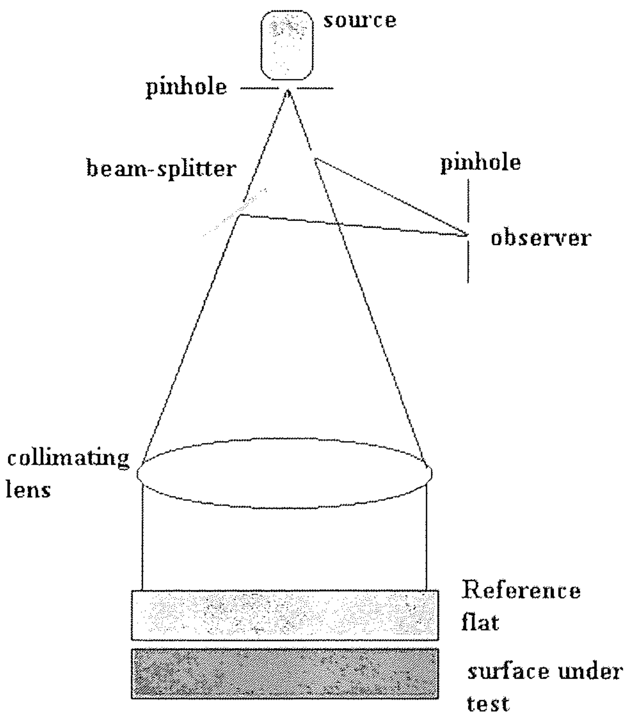


Figure AII.4. *The set-up for constructing a Fizeau interferometer*

The Fizeau interferometer is actually a modified Newton's interferometer (*Malacara, 1992)*. From the drawing of Figure AII.4 it is seen that it consists of a monochromatic light source with a pinhole placed in front of it. After that a beam divider is placed which is used to locate the fringes in order to be seen by the observer through a pinhole. After the beam divider a collimating lens is placed at a distance in order to have a collimating system. A known optical flat with its back surface antireflection coated, in order to isolate the reflection from the back surface, is used as reference and is mounted along with the collimating lens. The surface under test is kept below the reference flat with the air gap adjusted as small as possible. By tilting the surface under test fringes are observed due to the variation of the air gap between the reference and the surface under test. These are seen through the pinhole near the beam divider.

The use of Fizeau interferometer in optical testing

Such an interferometer was used for testing optical flats .It can test optical surfaces up to 240 mm diameter where a mercury mirror is used as the flatness standard, *(Bunnagel, et al., 1968)*, *(Schultz & Schwider, 1967)* tested cube corner and right angle prisms, while *Bruce & Cuninghame (1950)* tested curved surfaces convergent and divergent. In order to test curved surfaces the point source used should be located at the center of curvature of the reference lens or group of lenses *(Biddles, 1969)*. This type of instrument according to Biddles is a non-contact interferometer for testing steeply curved surfaces and it can also be used as a relative spherometer accurate to about one micron with respect to the master surface. *Kafri & Kreske (1988)* produced a device, which enables the combined operation of a moiré deflectometer, Fizeau interferometer and Schlieren device, with such a device is possible to compare the three methods and benefit from the advantages of each method.

Twyman-Green interferometer

The Twyman-Green interferometer is a variation of the Michelson interferometer *(Twyman (1918a), (1918b))*. This instrument was widely used to test optical components and especially large mirrors or large lenses and prisms. It consists of a point monochromatic source, which is placed at the focus of a lens L_1, which collimates the beam providing a uniform and coherent wave front. It also has a beam splitter (face A of the beam splitter reflects the light while face B does not, or it is placed at Brewster's angle but the light source should have a certain polarization) and two mirrors M_1 and M_2 just like the Michelson one. Another lens L_2 is used to form the image of the fringes so the observer can see them. Such an interferometer is shown in Figure AII.5.

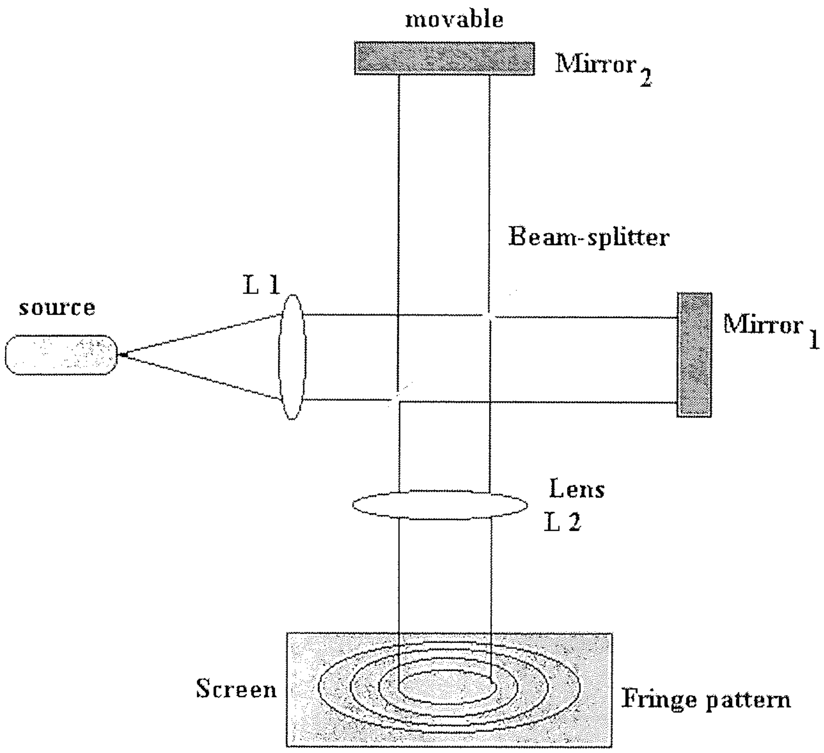


Figure AII.5. *The set-up for a Twyman-Green interferometer*

The use of Twyman-Green interferometer in optical testing

The Twyman-Green interferometer is a very useful instrument for testing prisms and microscope objectives *(Twyman & Green, 1916)* and *(Twyman, 1957)*. (*Thomas and Wyant, 1977)* made a complete study of the testing of cube corner prisms. Also this instrument was used in testing lenses *(Van Heel & Simons, 1967) (Bruning et al., 1974)* and camera objectives *(Twyman, 1919)*, including the measurement of the chromatic aberration *(Martin & Kingslake, 1923-24)*. In order to test large lenses *(Burch, 1940)* suggested using a concave mirror on one of the arms of the interferometer and the large lens with a flat mirror in front of the it on the other arm, instead of using a large beam splitter, larger than the lens tested. *Kocher (1972)* also proposed a modified type in order to test large aperture optical systems by utilizing a thick beam splitter substrate. It is worth mentioning that according to *Munnerlyn (1972)* the refractive index of a simple convex lens can be measured utilizing a Twyman-Green interferometer. *Kingslake (1926-27)* made an analysis of the interferograms due to primary aberrations (spherical, coma, defocusing, etc.).

Mach Zender interferometer

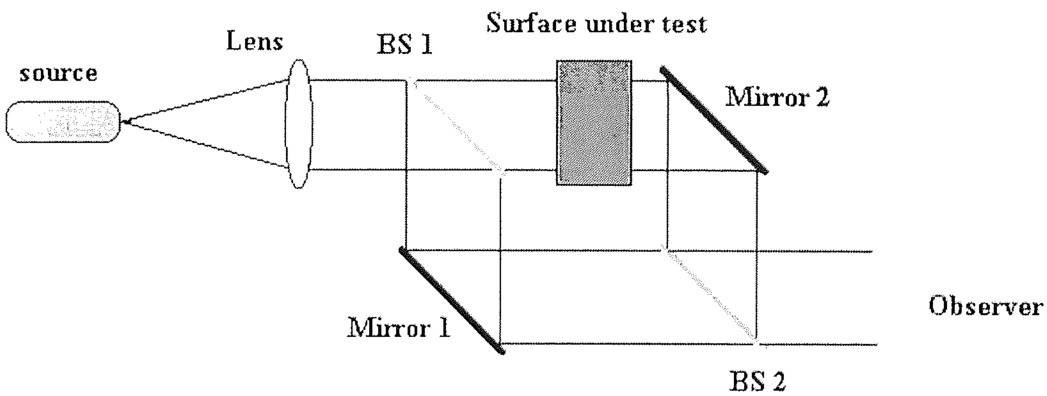


Figure AII.6. *The schematic layout of a Mach-Zehnder interferometer*

It is an instrument that resembles Michelson interferometer. Figure AII.6. shows how the instrument is arranged. The beam from the source strikes a glass plate BS_1 (partially silvered) at a certain angle. Part of the beam is reflected to Mirror M_1 and part of it transmitted to the mirror M_2 after passing from the tested surface. The light from mirror M_1 is reflected to a glass plate BS_2 passing through it. On the other hand the light from mirror M_2 is reflected to the glass plate BS_2. At BS_2 the two paths of light recombine producing a fringe pattern. Such an instrument is useful for studying slight changes of refractive index, *Hariharan (1992)*.

This interferometer provides an interference pattern with the light beam only making a single-pass through a test element. Such an interferometer is used as a measuring tool in studying temperature distribution in flames and plasmas, gas flow and gas temperature changes.

The use of Mach-Zehnder interferometer in optical testing

The most important literature for such an instrument comes from *Wiharjo (1995)* where he used a technique with a Mach-Zehnder interferometer for measuring oblique astigmatism error of ophthalmic lenses. By simulating the actual conditions of the eye, the effects of the lens power, the pupillary aperture size and viewing distance were calculated. Another interesting paper is the one by *Mohr (1989)* where he used such an instrument to measure progressive lenses. The interferometric measuring result has been obtained by comparing the lens under test with a reference lens "the aspheric reference surface".

Fabry Perot interferometer

Interference is feasible also with more than two beams. This is called multi-beam interference and it is possible to achieve with an instrument such as Fabry-Perot interferometer (*Fabry-Perot, 1897*), (*Chandler, 1951*). Such an interferometer is seen in Figure AII.7. It consists of two pieces of flat glass plates one is fixed while the other is movable, facing each other, where the inner surfaces are polished and highly reflecting coated by a metallic film of silver, gold or aluminum. The fringes that are produced are of equal inclination. Monochromatic light coming from a broad light source passes through the two glass plates. Any incident ray from the source is reflected into a series of parallel-transmitted rays, which are brought together in order to interfere by means of a lens. (*Jenkins & White, 1976*).

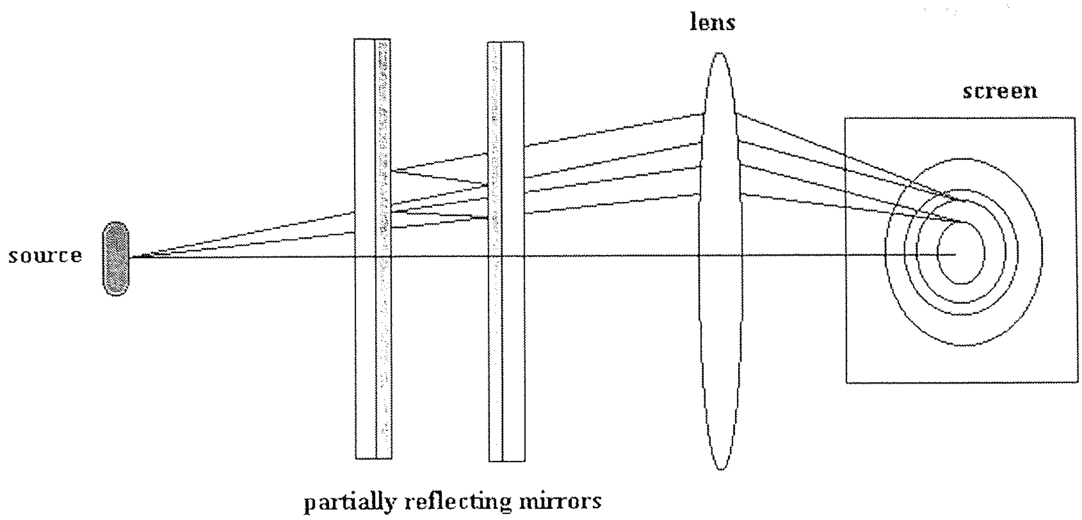


Figure AII.7. *The Fabry-Perot interferometer*

The use of Fabry-Perot interferometer in optical testing

In 1969 *Hodgkinson (1969)* was the first to use Fabry- Perot interferometer for the study of surface defects. *Schultz (1967)* used the instrument for surface evaluation and measurements.

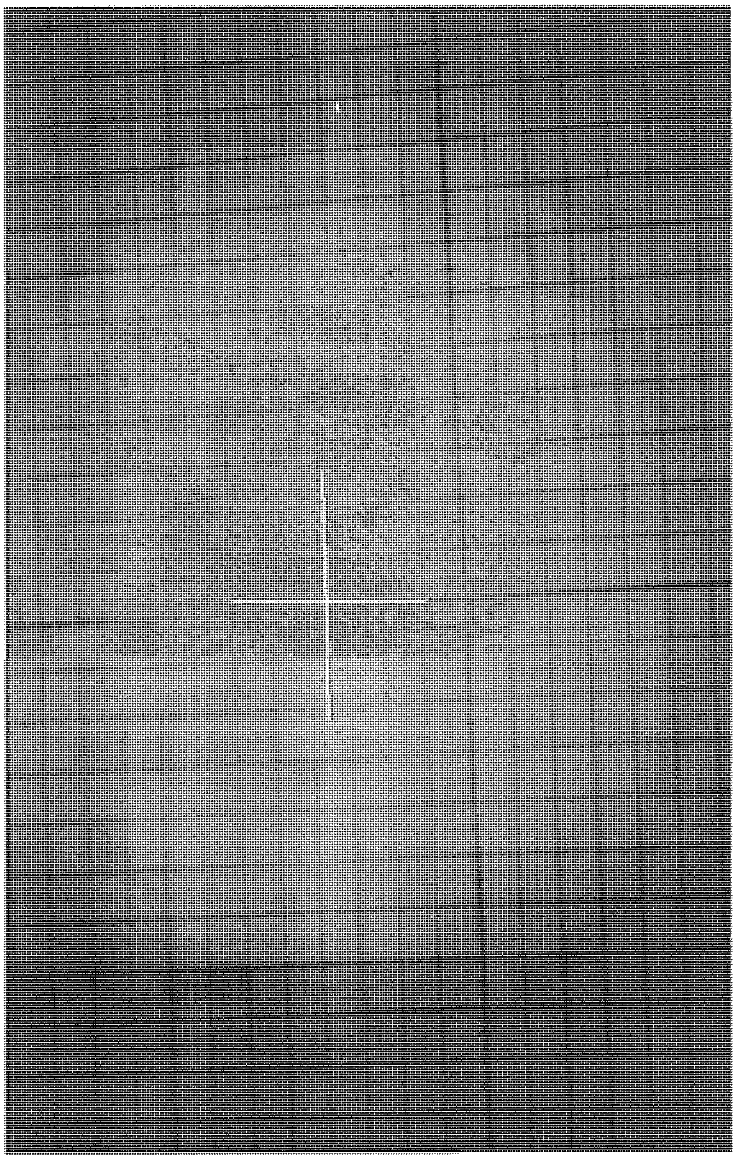
Lateral shearing interferometry

Another important field of interferometry that we have not yet discussed is "Lateral shearing interferometry" *(Murty, (1964b).* Basically the method consists of displacing the defective wave front by a small amount and obtaining interference pattern between the original and the displaced wave fronts. This eliminates the need for a reference surface. An interferometer of such a technique is known as Murty interferometer. Such an interferometer was used by *Kasana & Rosenbruch (1983)* and *De Vany (1971)* to measure the homogeneity of the optical materials tested and specifically to determine the refractive index of a lens. *Shukla et al (1990), Shukla & Malacara (1997)* with such an interferometer determined the homogeneity of optical elements measure refractive index of glasses and liquids, measure the radius of curvature and determine the power of ophthalmic lenses. A very important paper was given by *Wyant & Smith (1975)* where a lateral shearing interferometer is used directly to measure the power variation of an ophthalmic lens. With such an interferometer they measure different parts of the lens can be measure or even the whole lens or different segments of a multifocal.

Appendix III.

Inteferograms of trial lenses

The fringe patterns photographed for trial lenses measured with an interferometric technique. The first photos were taken using a Michelson interferometer. It is seen from the results that the initial wave front produced is astigmatic and this is interfering with the results taken from the trial lenses measured



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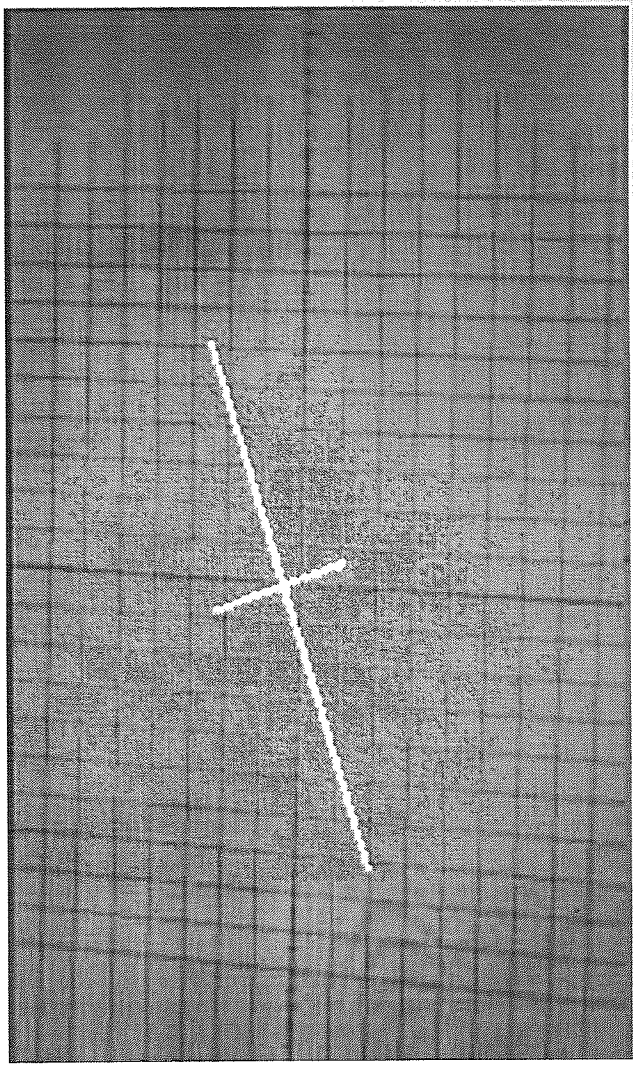

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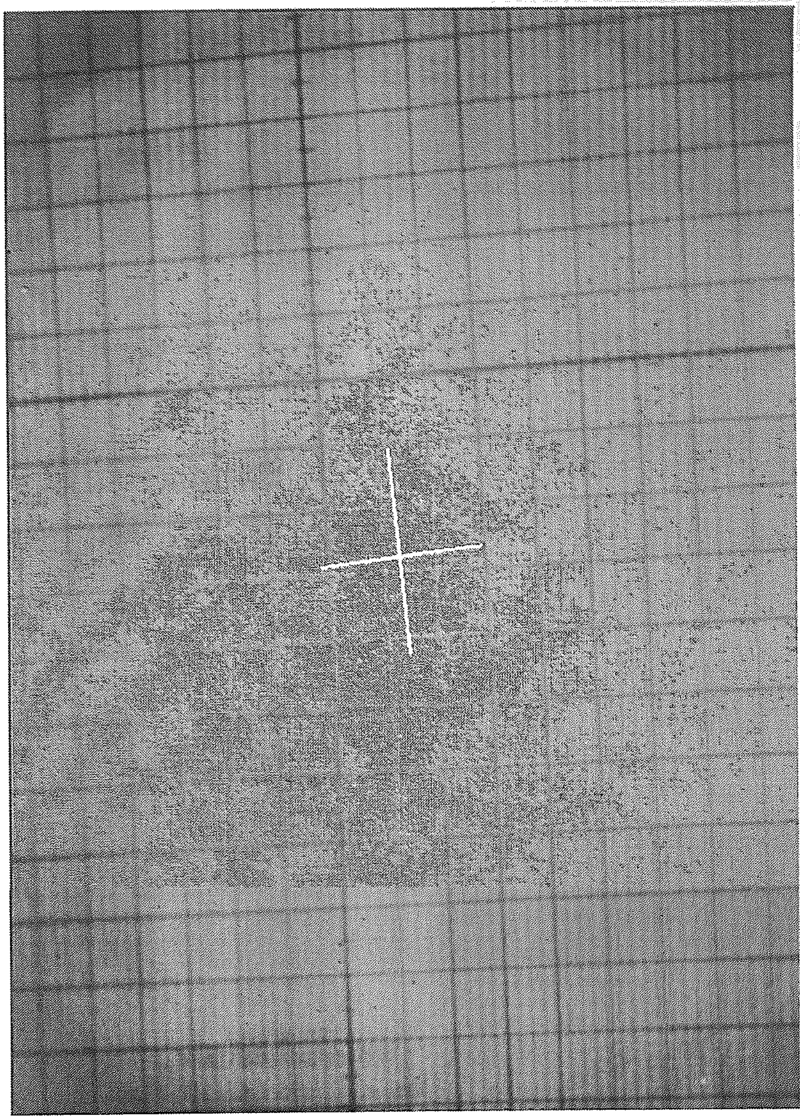

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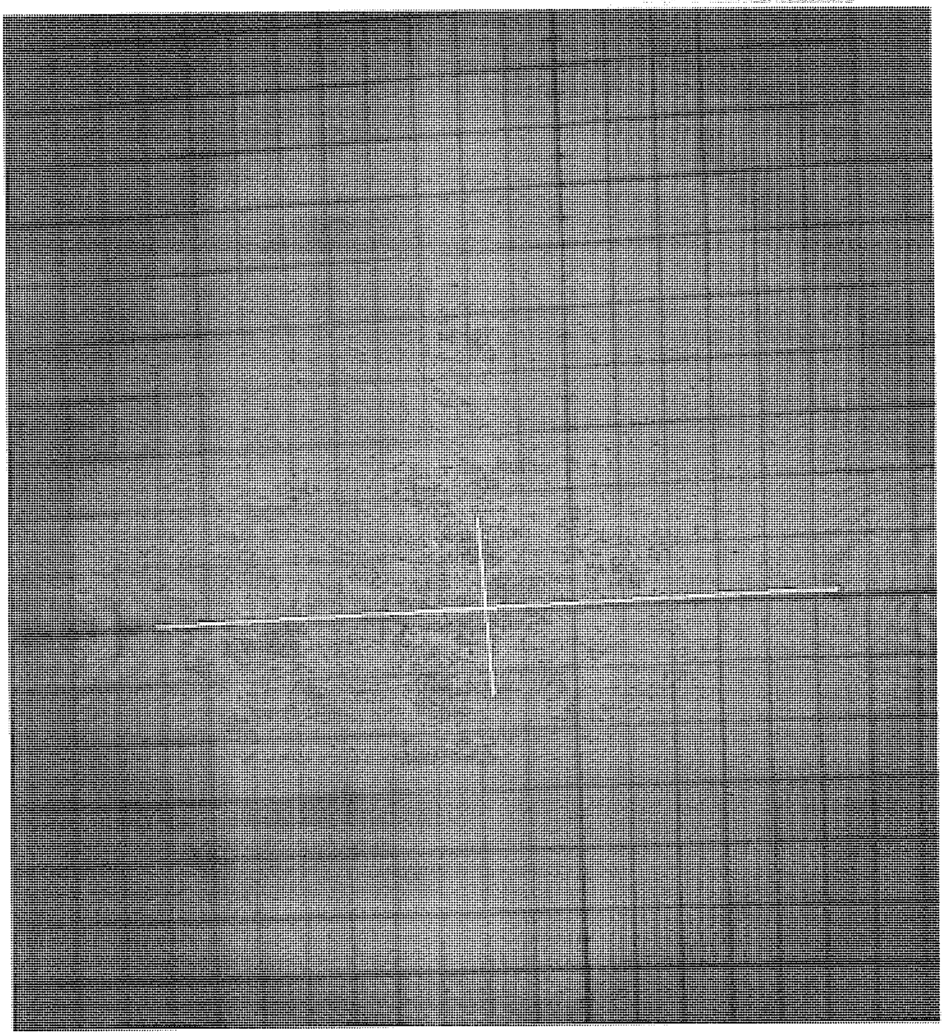

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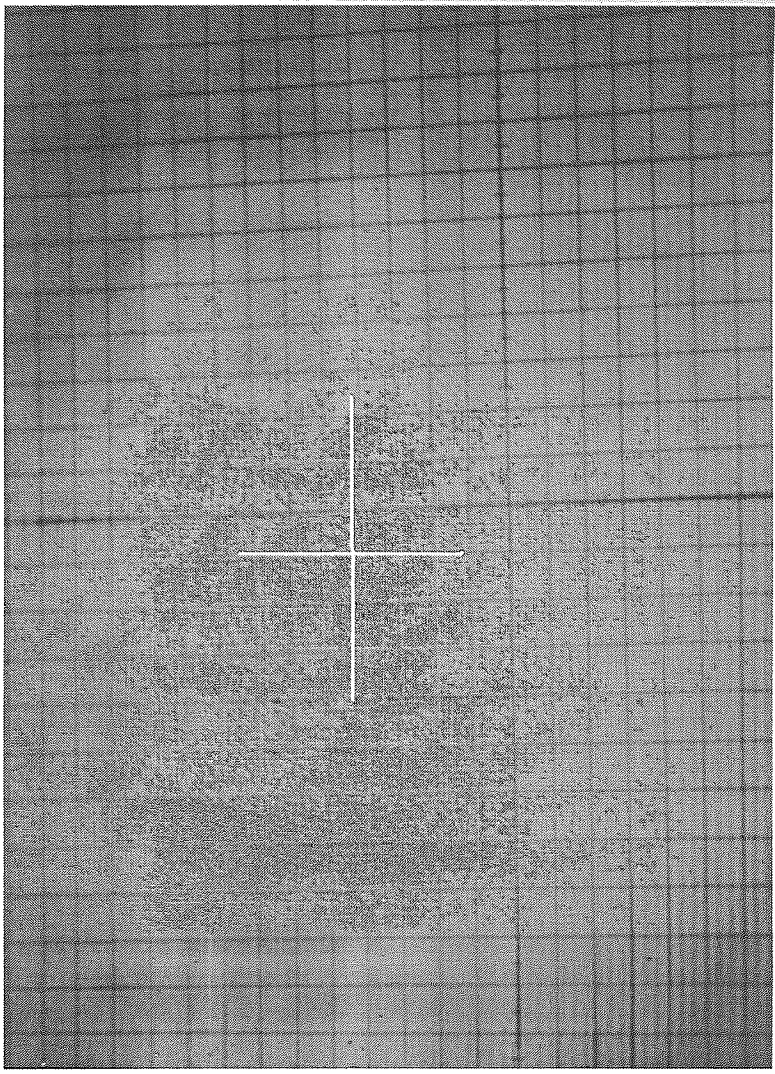

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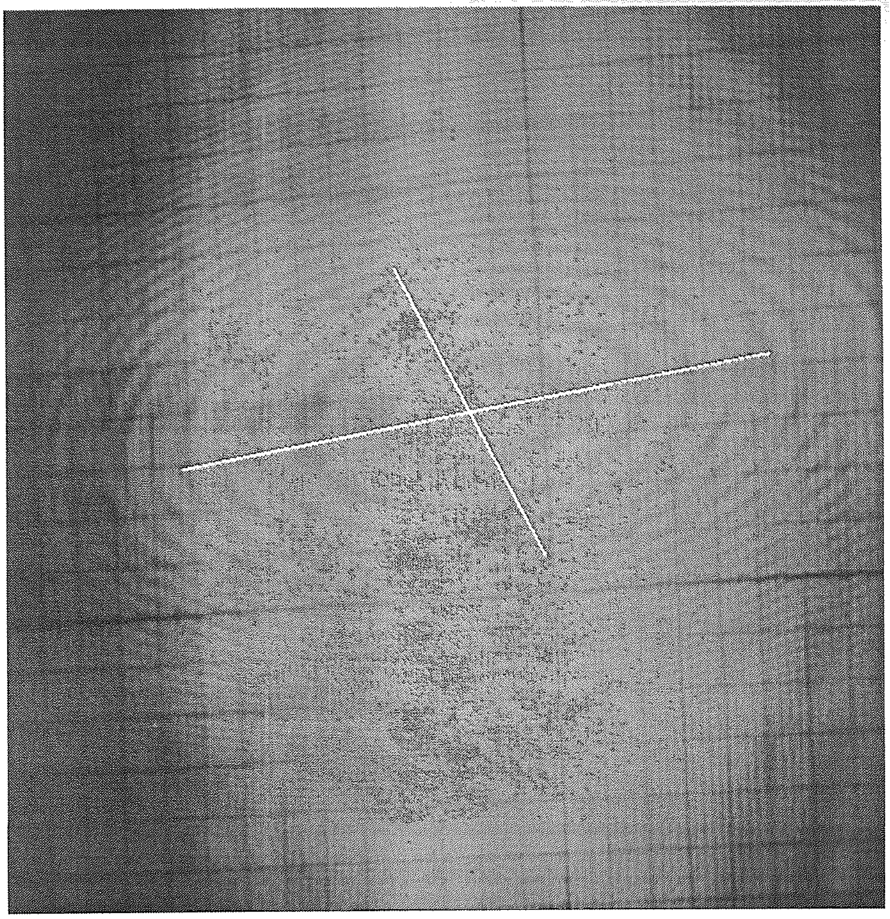

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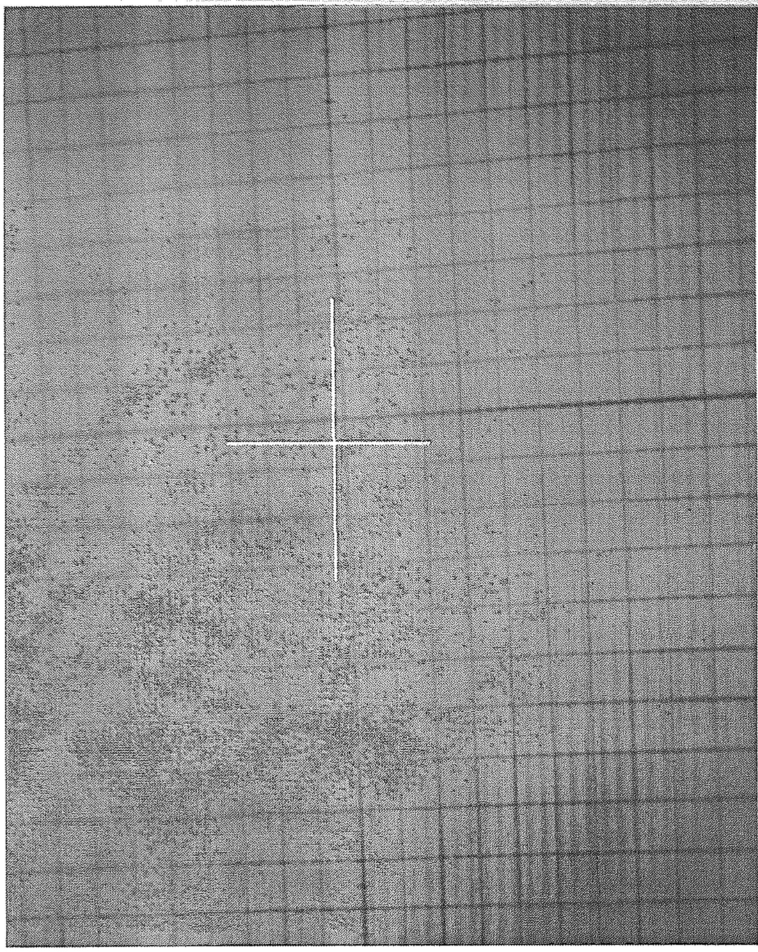

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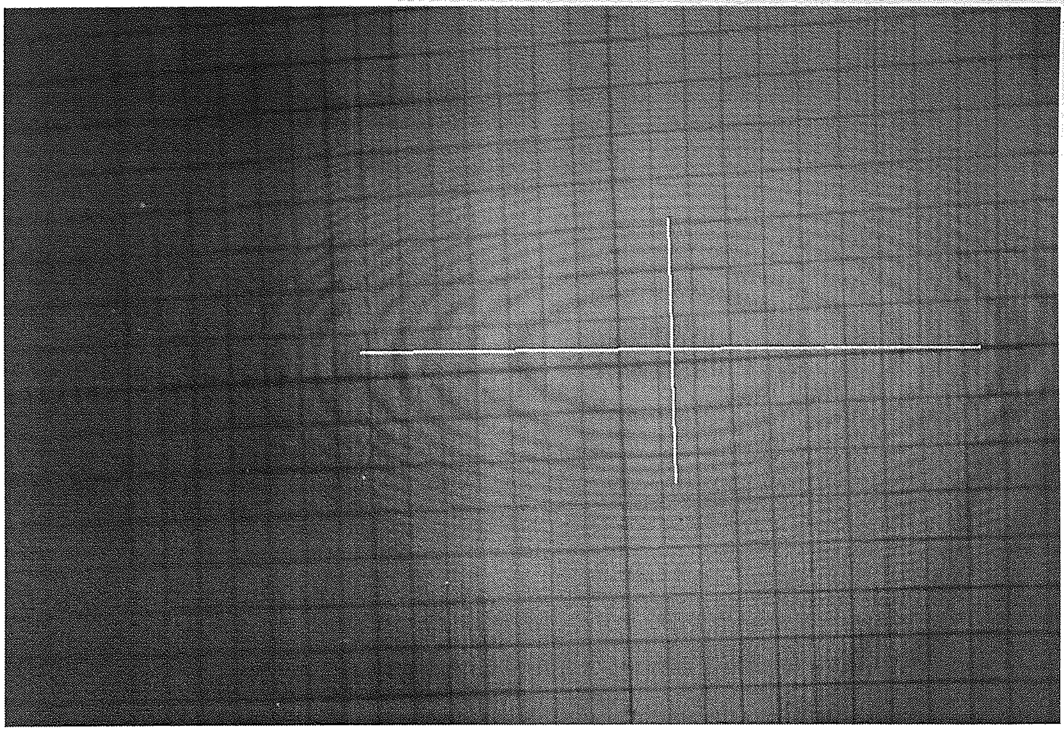

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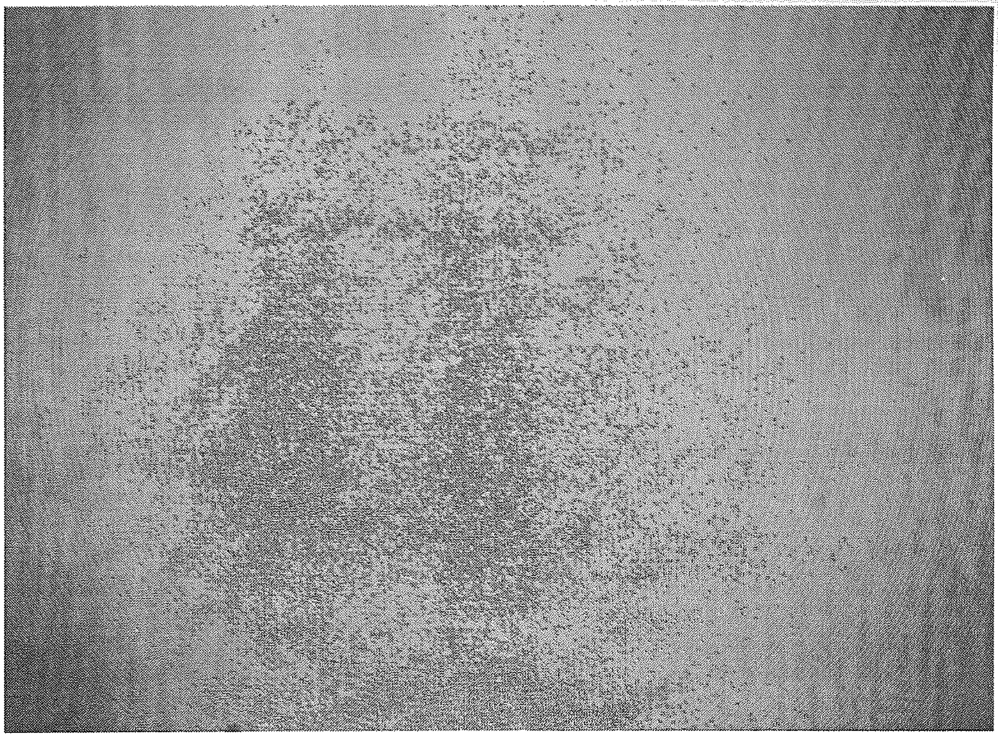
The fringe patterns of trial lenses measured with the Twyman-Green interferometer.



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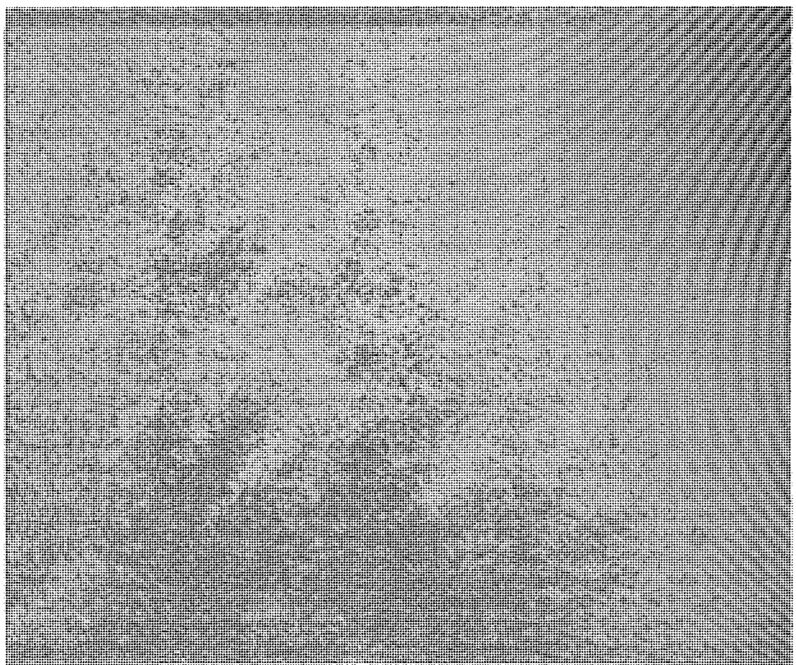

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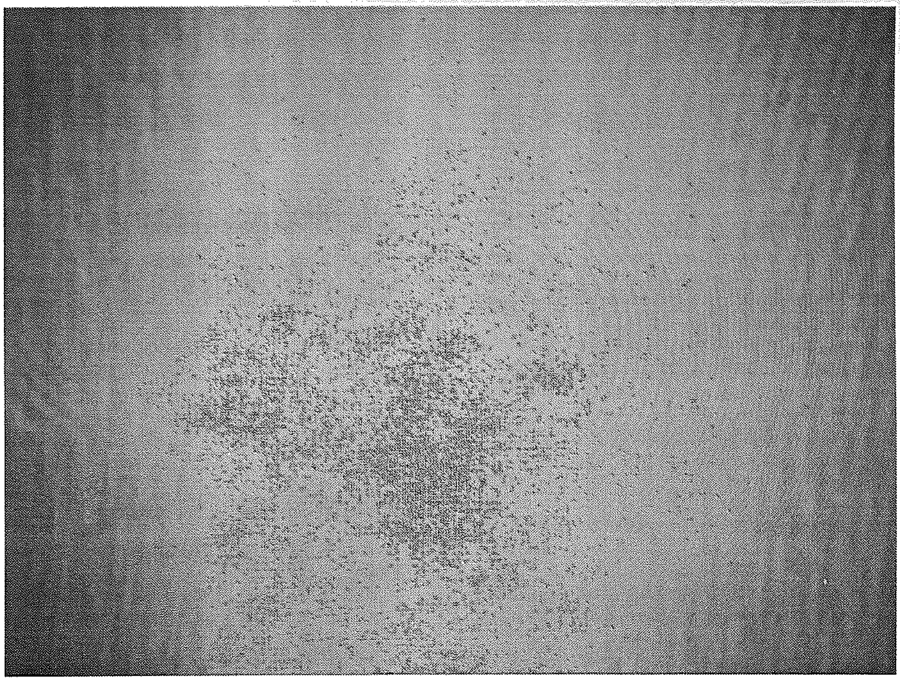

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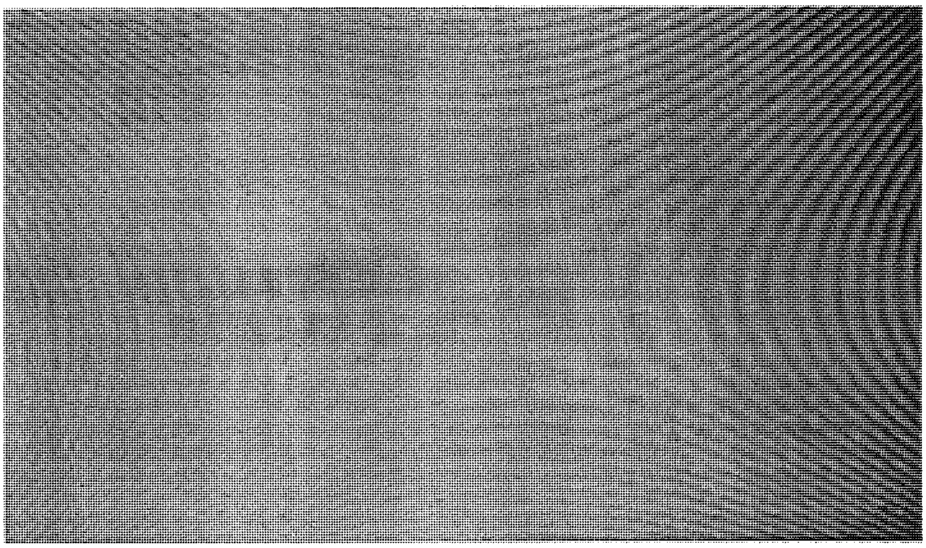

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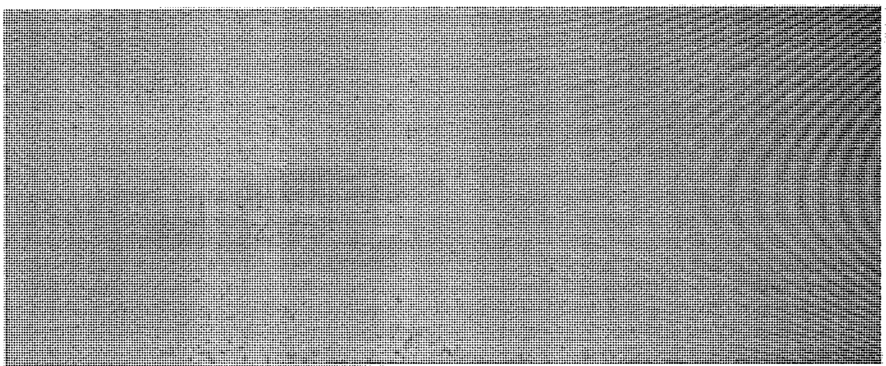

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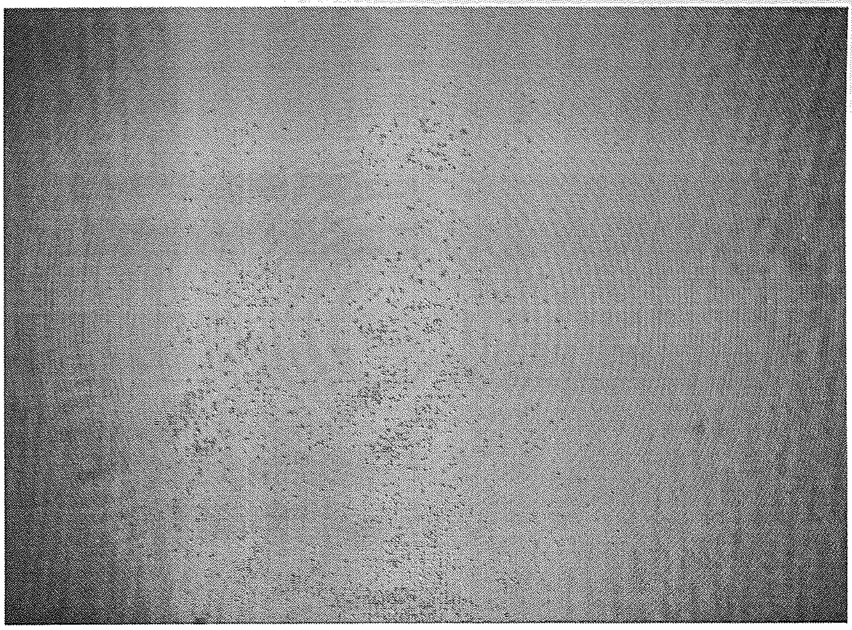

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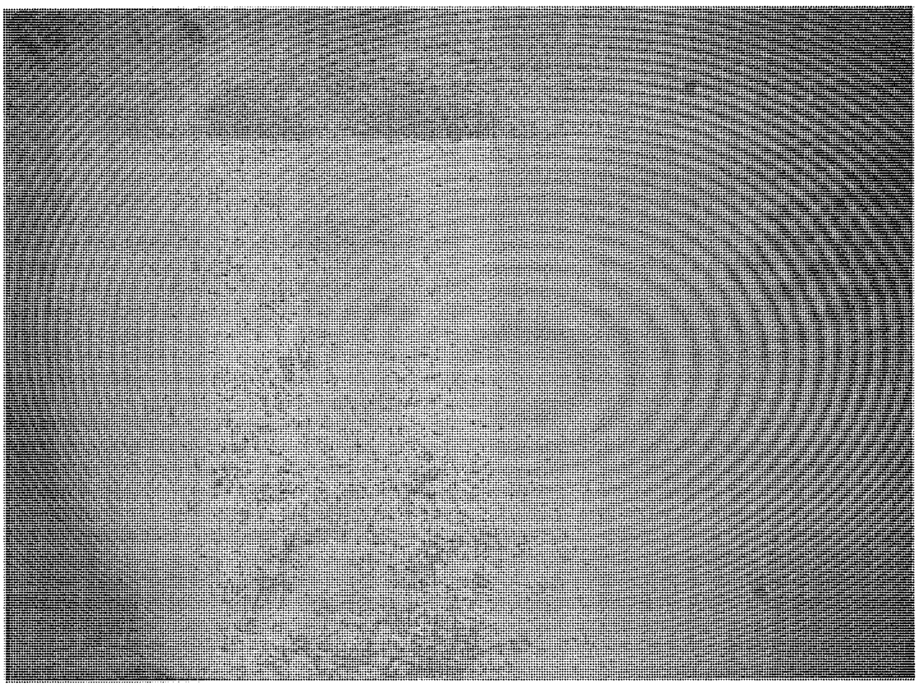

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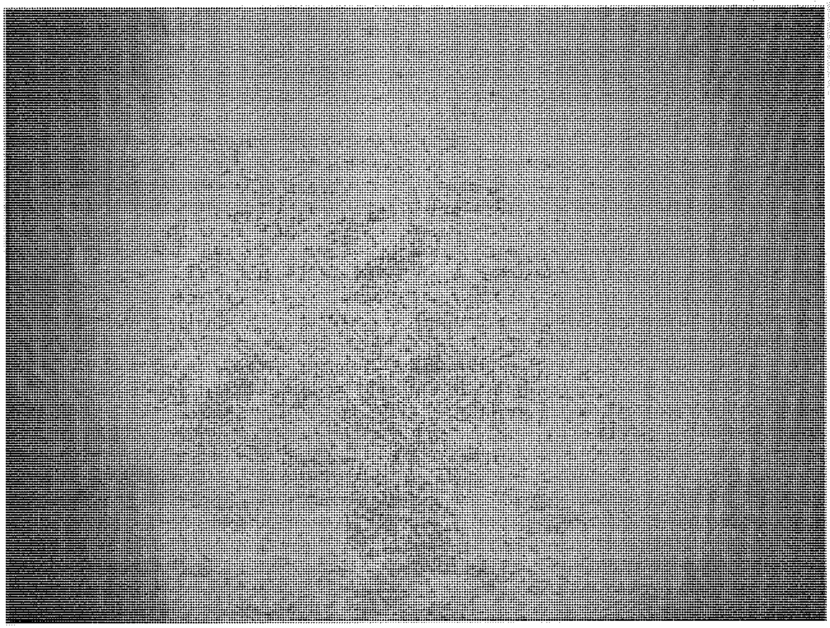

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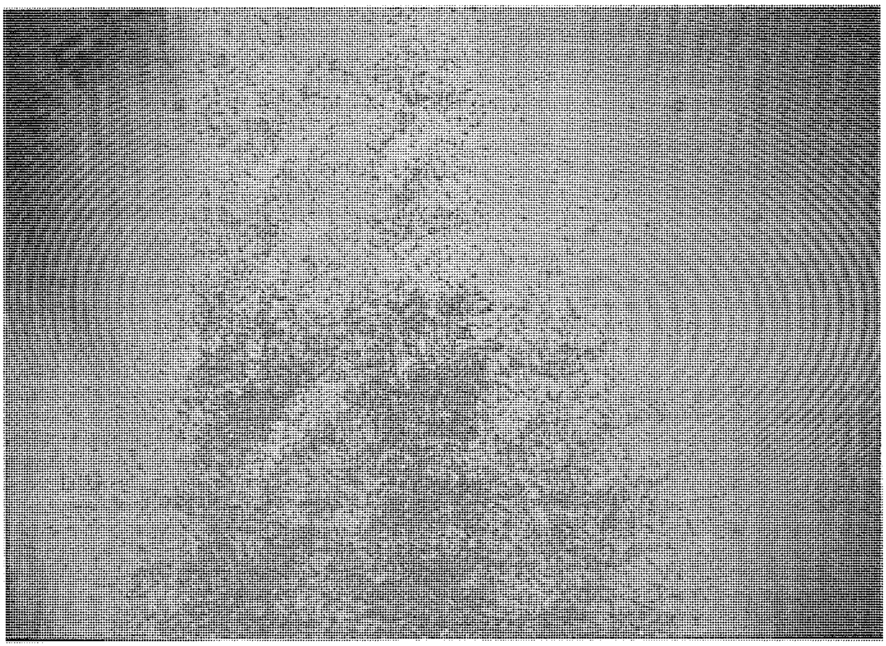

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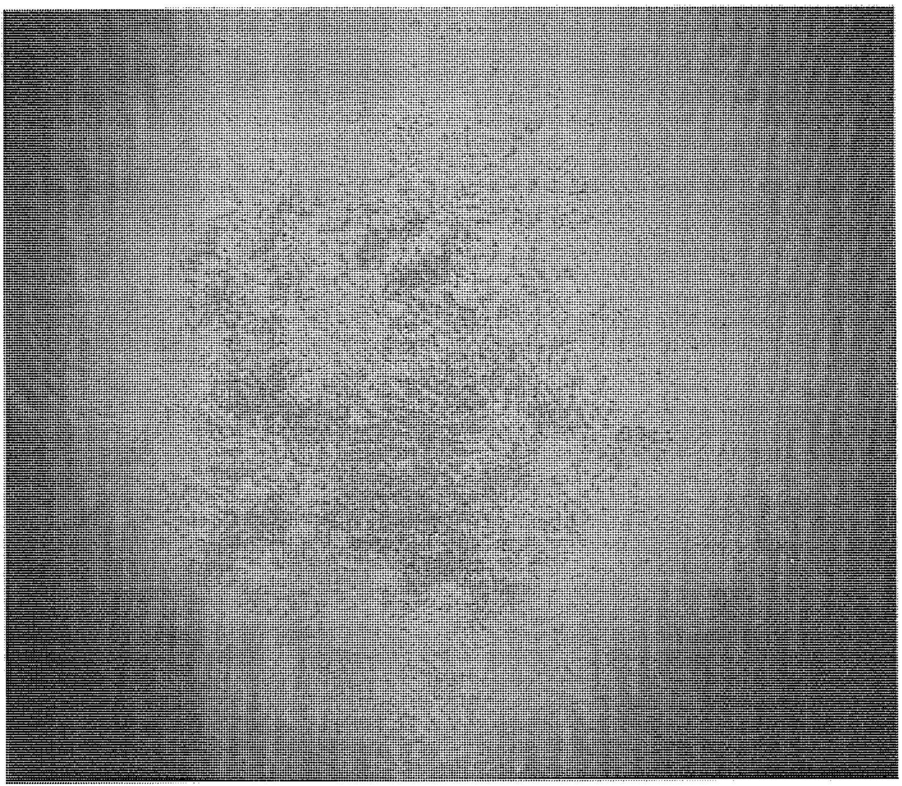

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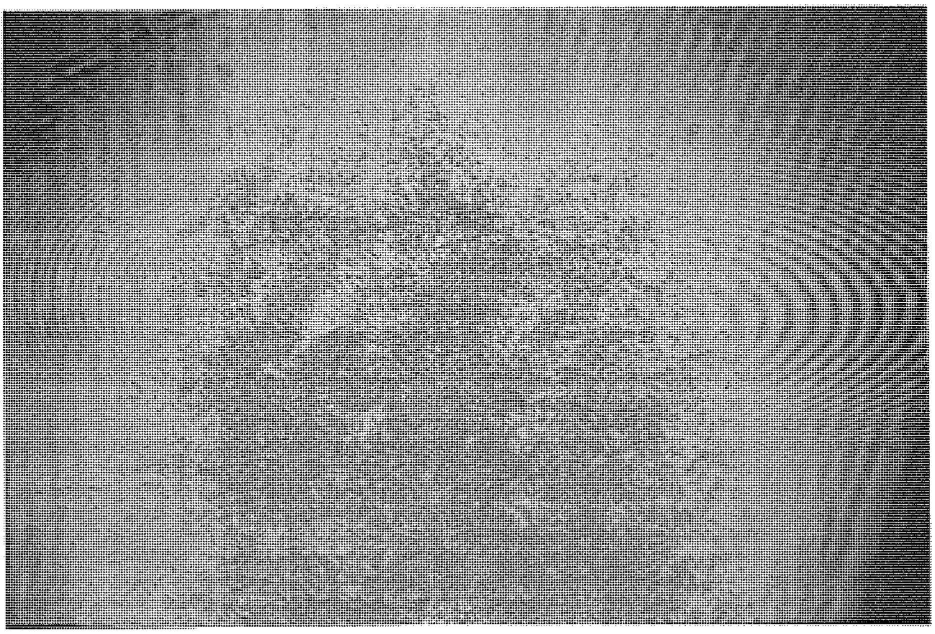

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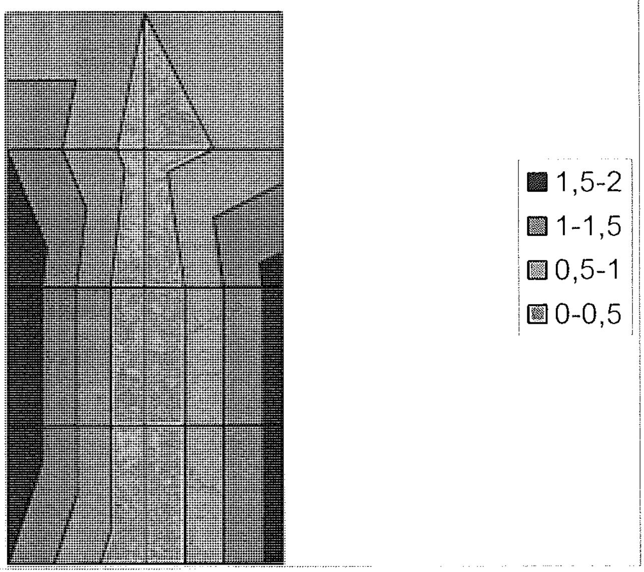
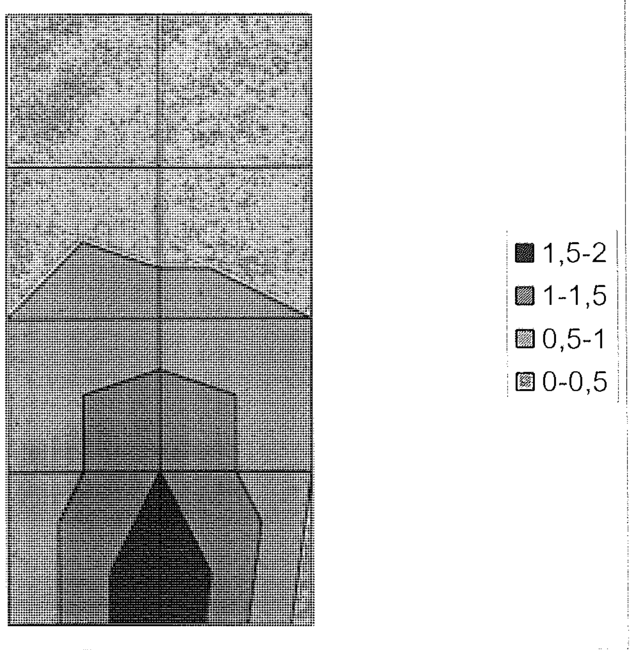
Appendix IV.

Results of progressive addition lenses

AOptical PRO (Interferometer)

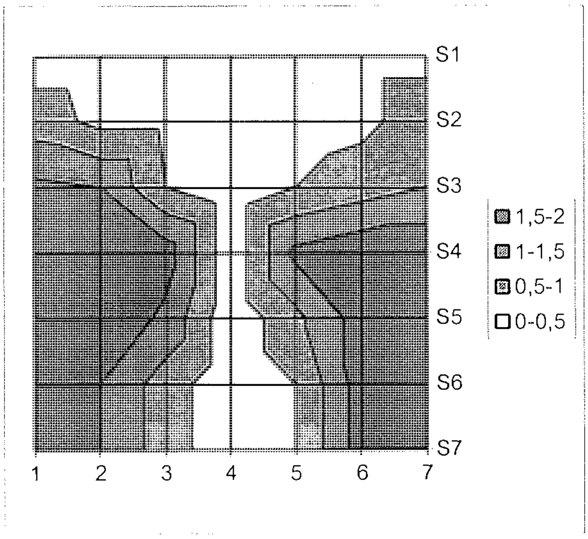
plano	Add 2.00	AO Pro												
	Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
9	0,25	0,5	**16**	0,25	1,5	**23**	0,5	2	**30**	0,5	2	**37**	0,5	1,5
11	0	0,5	**18**	0	0,25	**25**	0,75	0	**32**	1,5	0	**39**	2	0
13	0	0,5	**20**	0	0,75	**27**	0,5	1,75	**34**	0,5	1,75	**41**	0,25	1,75

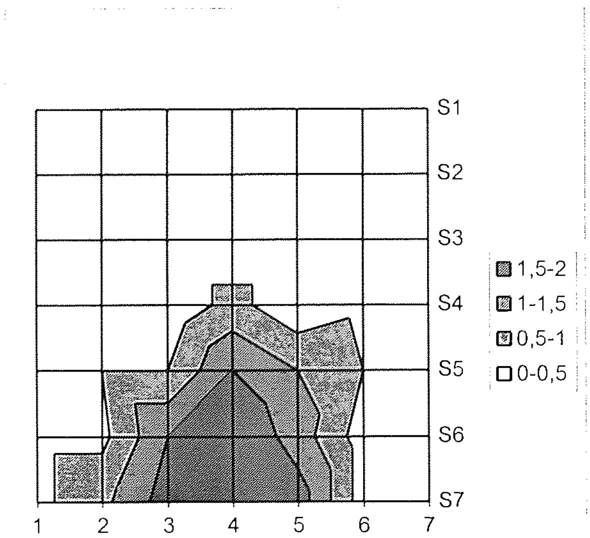




AOptical PRO (Auto-focimeter)

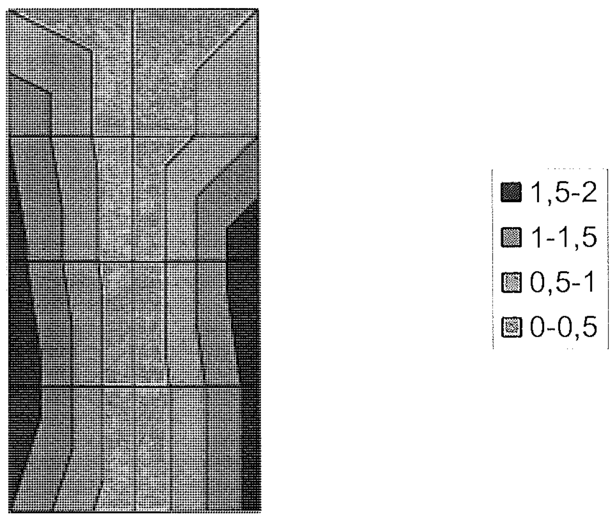
plano	Add 2.00																			
	Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
1	0	0,25	**8**	0	0,75	**15**	0	1,62	**22**	0,25	1,87	**29**	0,5	1,75	**36**	0,37	1,5	**43**	0,37	1,5
2	0	0,25	**9**	0,12	0,37	**16**	0,12	1,5	**23**	0,37	1,87	**30**	0,5	2	**37**	0,37	1,5	**44**	0,87	1,5
3	0	0,12	**10**	0,12	0,37	**17**	0,12	0,5	**24**	0,12	1,75	**31**	0,5	1,37	**38**	1,5	0,75	**45**	1,75	0,75
4	0	0,37	**11**	0	0	**18**	0,12	0,12	**25**	0,67	0,12	**32**	1,5	0,12	**39**	2	0,12	**46**	2	0,12
5	0	0,12	**12**	0	0,25	**19**	0,12	0,5	**26**	0,12	1,62	**33**	1	0,87	**40**	1,25	0,5	**47**	1,75	0,5
6	0	0,37	**13**	0	0,37	**20**	0	0,75	**27**	0,37	1,87	**34**	0,5	1,75	**41**	0,25	1,75	**48**	0,25	1,75
7	0	0,37	**14**	0,12	0,75	**21**	0	1	**28**	0,37	1,87	**35**	0,5	2	**42**	0,25	1,75	**49**	0,25	1,75

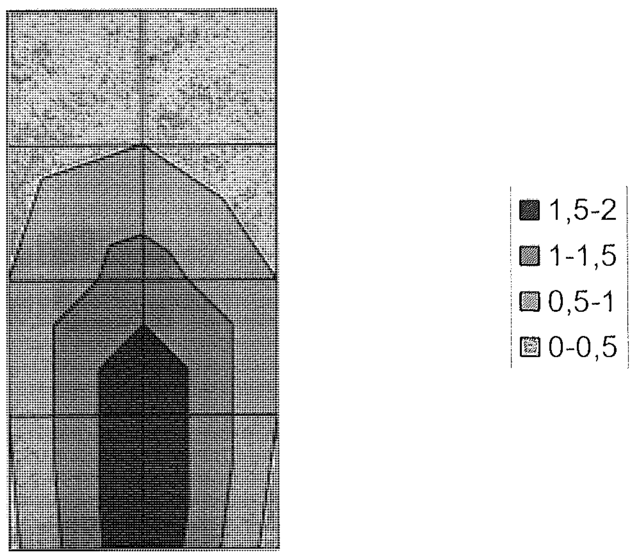




AOptical Compact (Interferometer)

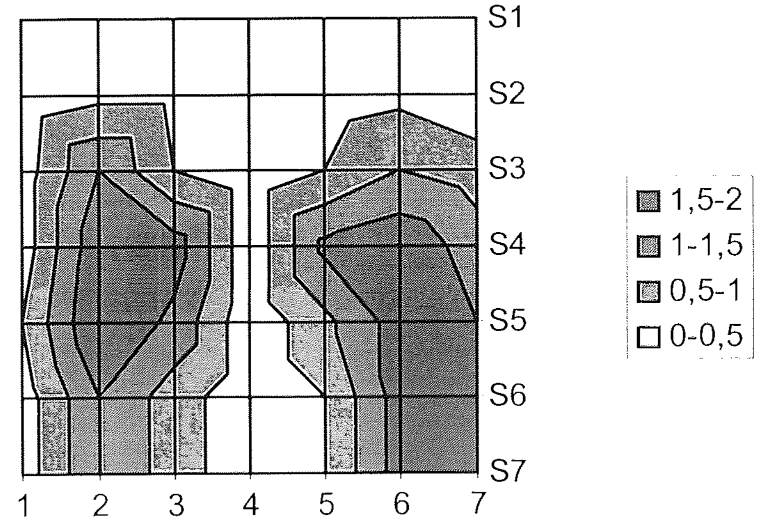
plano	Add 2.00	Compact												
	Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
9	0,25	0,5	16	0,25	1,5	23	0,5	1,75	30	0,5	2	37	0,37	1,5
11	0,5	0	18	0,5	0	25	1,25	0	32	2	0	39	2	0
13	0	0,5	20	0	1	27	0,5	2	34	0,5	1,75	41	0,25	1,75

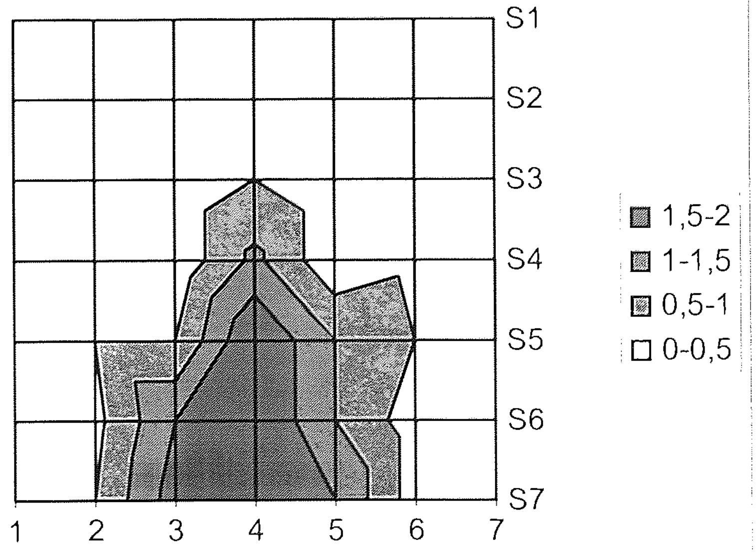




AOptical Compact (Auto-focimeter)

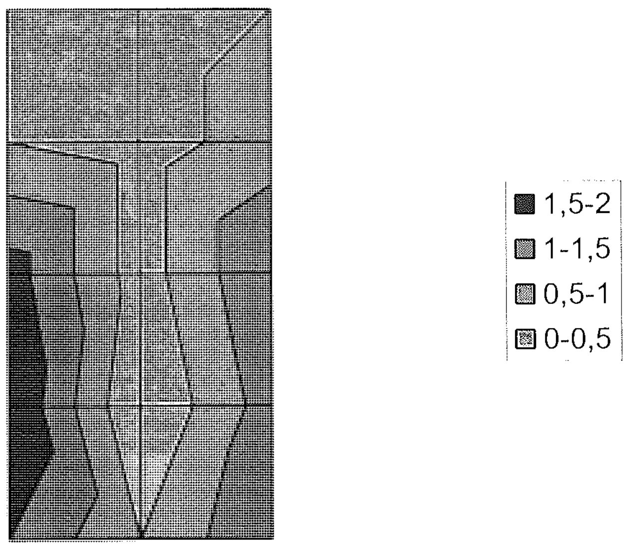
plano	Add 2.00																			
	Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
1	0	0,12	**8**	0	0,12	**15**	0	0,25	**22**	0,25	0,25	**29**	0,5	0,5	**36**	0,37	0,25	**43**	0,37	0,25
2	0	0,25	**9**	0,12	0,37	**16**	0,12	1,5	**23**	0,37	1,87	**30**	0,5	2	**37**	0,37	1,5	**44**	0,5	1,5
3	0	0,12	**10**	0,12	0,37	**17**	0,12	0,5	**24**	0,12	1,75	**31**	0,5	1,37	**38**	1,5	0,75	**45**	1,75	0,75
4	0,1	0,37	**11**	0,37	0	**18**	0,5	0,12	**25**	1,12	0,12	**32**	2	0,12	**39**	2	0,12	**46**	2	0,12
5	0	0,12	**12**	0	0,25	**19**	0,12	0,5	**26**	0,12	1,62	**33**	1	0,87	**40**	1	0,5	**47**	1,5	0,5
6	0	0,37	**13**	0	0,37	**20**	0	1	**27**	0,37	1,87	**34**	0,5	1,75	**41**	0,25	1,75	**48**	0,25	1,75
7	0	0,12	**14**	0,12	0,12	**21**	0	0,75	**28**	0,37	1,25	**35**	0,5	1,5	**42**	0,25	1,5	**49**	0,25	1,5

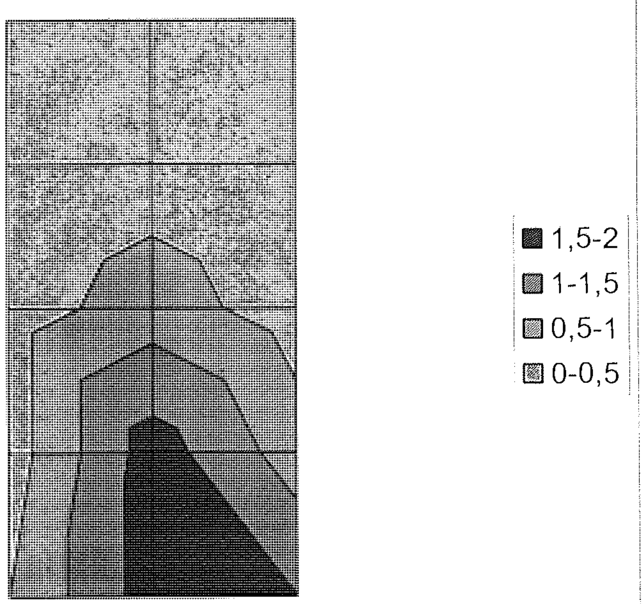




Essilor Varilux Comfort (Interferometer)

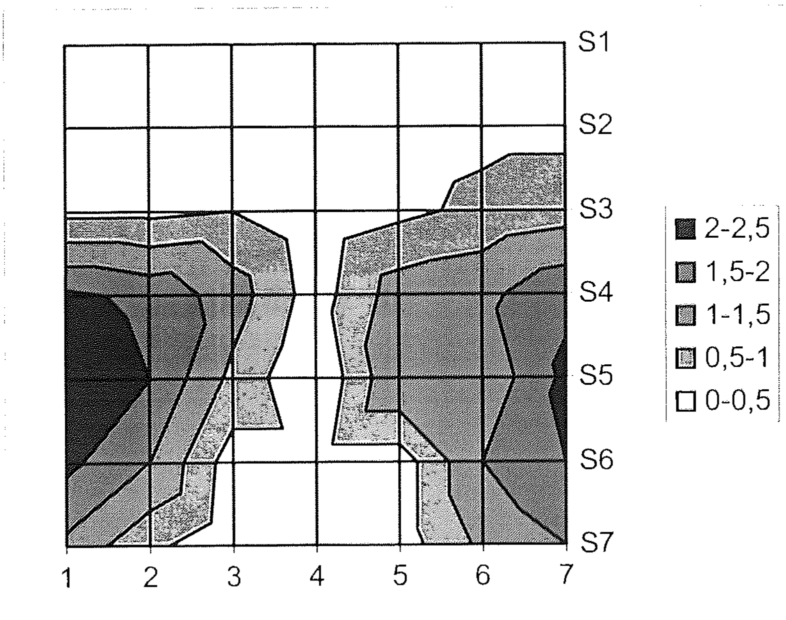
plano	Add 2.00	Comfort													
	Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
9	0,25	0,25	**16**	0	0,5	**23**	0,25	1,75	**30**	0,25	2	**37**	0,5	1,5
11	0,25	0,25	**18**	0,25	0,25	**25**	0,75	0,25	**32**	1,75	0	**39**	1,75	0,5
13	0	0,5	**20**	0	0,75	**27**	0,25	1,5	**34**	0,75	1,25	**41**	1,5	1,5

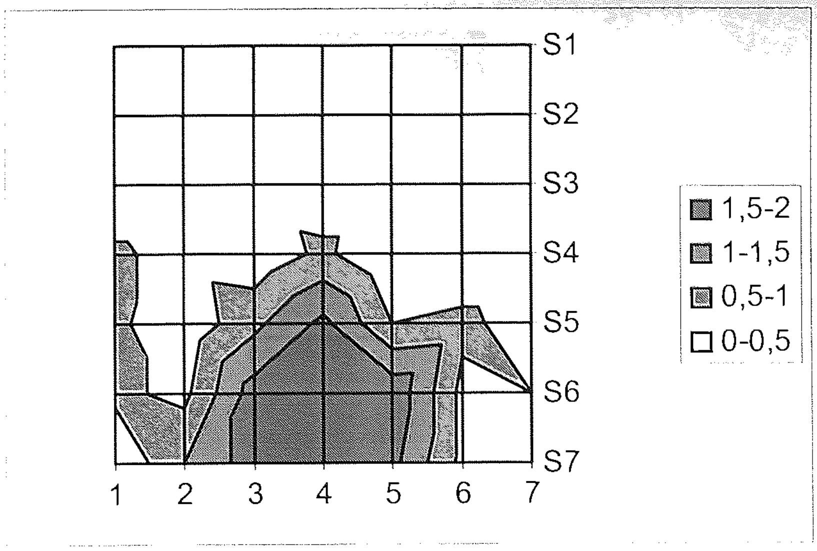




Essilor Varilux Comfort (Auto-focimeter)

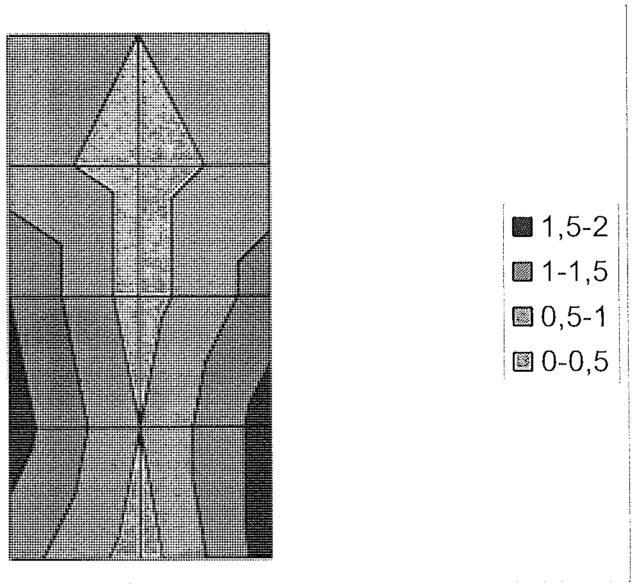
	plano	*Add 2.00*																			
	Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
1	0	0,25	**8**	0,25	0,25	**15**	0	0,37	**22**	0,62	2,12	**29**	0,62	2,37	**36**	0,6	2,1	**43**	0	1,37
2	0	0,25	**9**	0,25	0,25	**16**	0	0,37	**23**	0,25	1,87	**30**	0,12	2	**37**	0,4	1,5	**44**	1	0,62
3	0	0,25	**10**	0,25	0,25	**17**	0,25	0,5	**24**	0,12	1,25	**31**	0,87	0,87	**38**	1,8	0,3	**45**	1,8	0,12
4	0	0,12	**11**	0,12	0,25	**18**	0,12	0,12	**25**	0,62	0,25	**32**	1,62	0	**39**	1,9	0,3	**46**	1,9	0,12
5	0	0	**12**	0	0,25	**19**	0,12	0,37	**26**	0	1,25	**33**	0,5	1,5	**40**	1,9	0,3	**47**	1,6	0,25
6	0,12	0,12	**13**	0	0,37	**20**	0	0,62	**27**	0,12	1,37	**34**	0,62	1,12	**41**	0,4	1,5	**48**	0,4	1,12
7	0,12	0,12	**14**	0	0,37	**21**	0,37	0,75	**28**	0,12	1,87	**35**	0,25	2,12	**42**	0,5	2	**49**	0	1,5

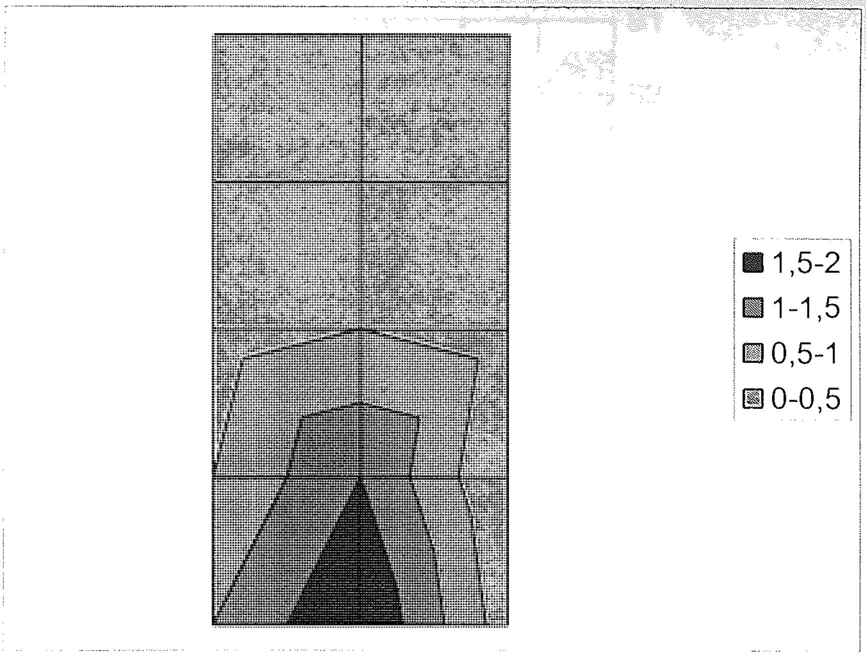




Essilor Varilux Panamic (Interferometer)

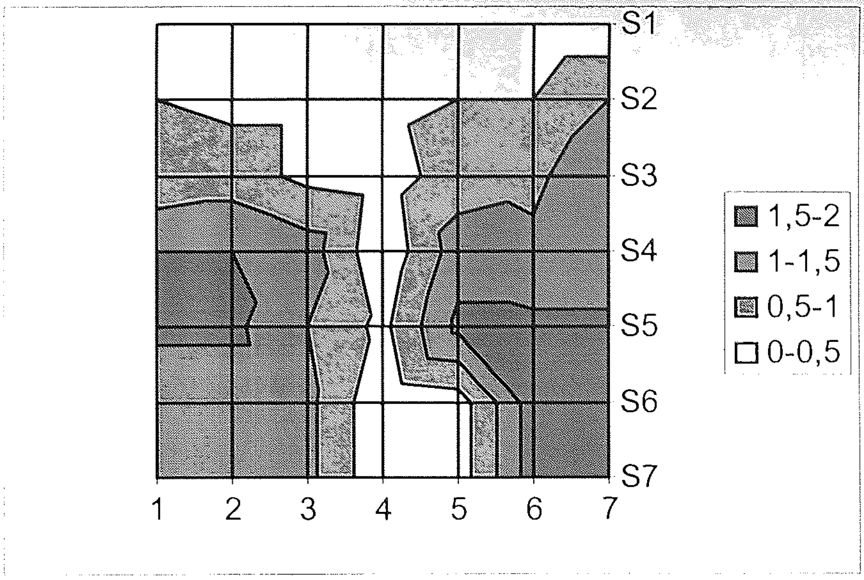
plano	Add 2.00	Panamic												
	Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
9	0	0,5	**16**	0,25	0,75	**23**	0,25	1,5	**30**	0,5	1,75	**37**	1	1,25
11	0,25	0,5	**18**	0,25	0,25	**25**	0,5	0,25	**32**	1,5	0,5	**39**	2	0,25
13	0,25	0,5	**20**	0,25	0,75	**27**	0,25	1,25	**34**	0	1,75	**41**	0,25	1,75

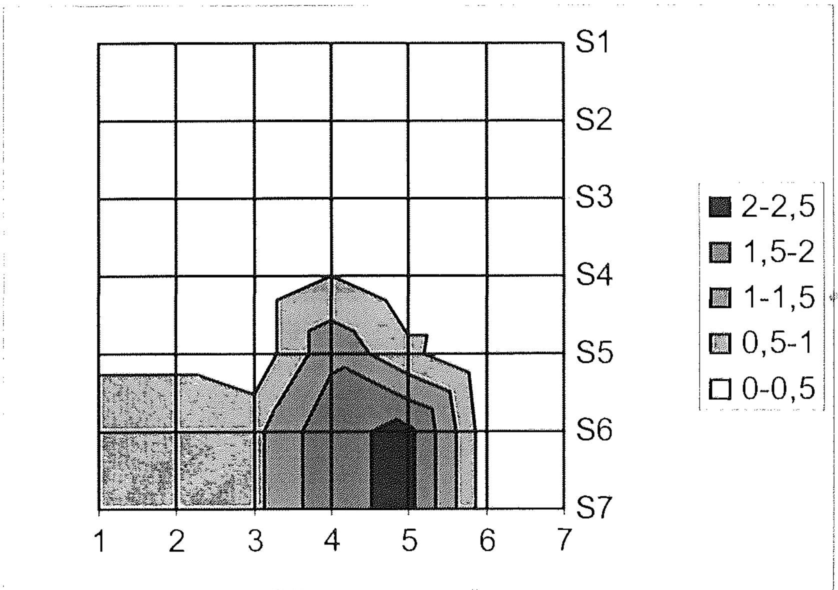




Essilor Varilux Panamic (Auto-focimeter)

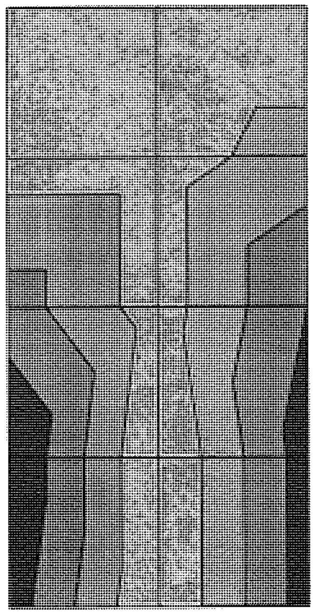
	plano	Add 2.00																		
	Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
1	0,25	0,25	8	0,25	0,5	15	0,12	0,62	22	0,12	1,5	29	0,37	1,62	36	0,87	1,12	43	0,87	1,12
2	0,25	0,25	9	0	0,37	16	0,13	0,75	23	0,12	1,5	30	0,37	1,62	37	0,87	1,12	44	0,87	1,12
3	0	0,12	10	0	0,37	17	0	0,37	24	0,12	1,25	31	0,12	1	38	0,87	1,12	45	0,87	1,12
4	0	0,12	11	0,13	0,37	18	0,13	0,25	25	0,5	0,12	32	1,37	0,37	39	1,87	0,12	46	1,87	0,12
5	0,13	0,37	12	0,12	0,5	19	0,13	0,75	26	0,12	1,25	33	0,62	1,62	40	2,12	0,25	47	2,12	0,25
6	0,12	0,12	13	0,12	0,5	20	0,25	0,87	27	0,12	1,12	34	0	1,62	41	0,25	1,75	48	0,25	1,75
7	0,12	0,12	14	0,25	1	21	0,25	1,5	28	0,12	1,12	35	0	1,62	42	0,25	1,75	49	0,25	1,75

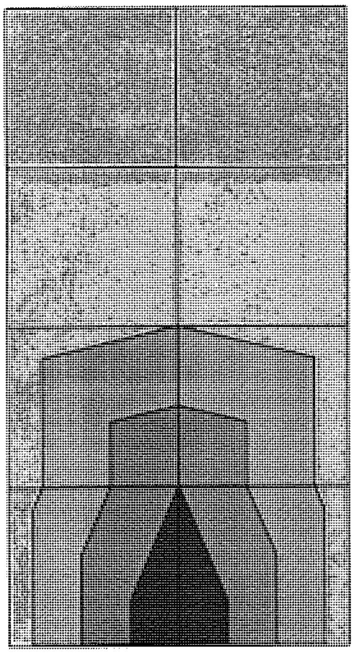




Hoya GP (Interferometer)

plano	Add 2.00 Sph	GP Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
9	0	0,25	**16**	0,25	0,25	**23**	0,25	1,25	**30**	0,25	2	**37**	0,25	1,75
11	0,25	0	**18**	0	0,25	**25**	0,5	0,25	**32**	1,5	0	**39**	2	0
13	0,25	0	**20**	0,25	0,75	**27**	0,25	1,5	**34**	0,25	1,75	**41**	0,25	1,75



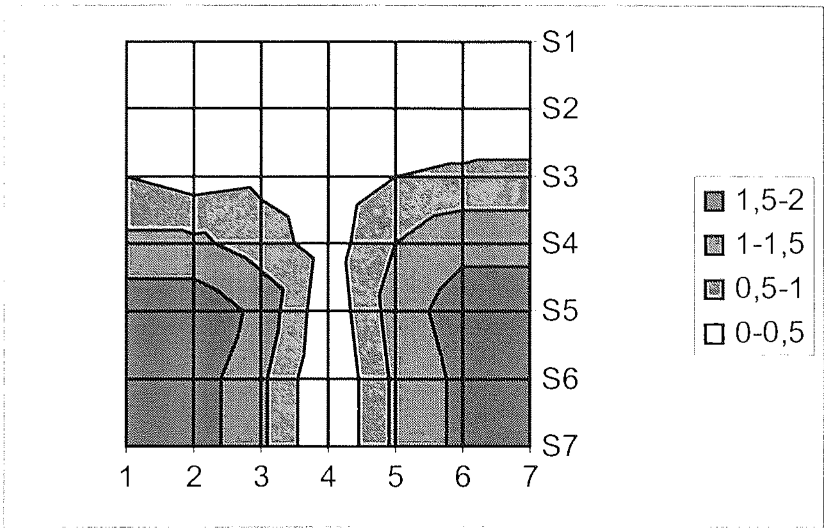


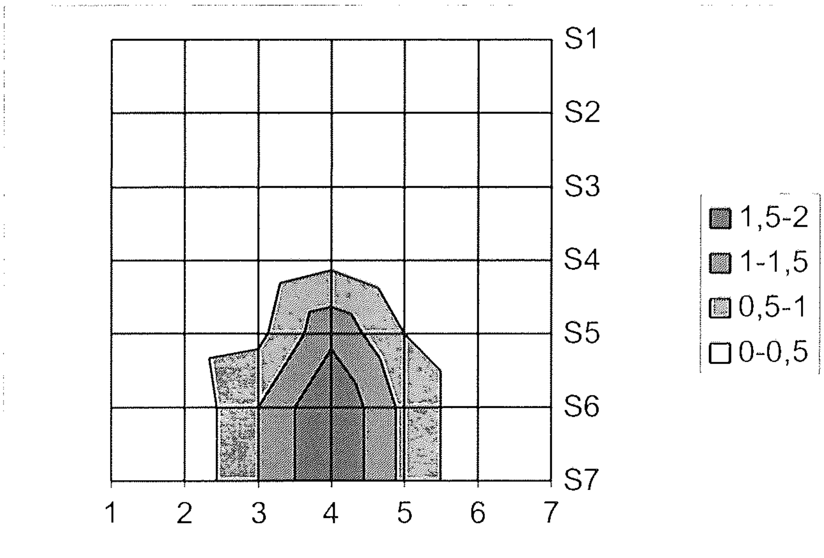
Hoya GP (Auto-focimeter)

plano Add 2.00

	Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
1	0,25	0,12	**8**	0,25	0,12	**15**	0,12	0,5	**22**	0,12	1,12	**29**	0,25	1,87	**36**	0,12	1,75	**43**	0,12	1,75
2	0,25	0,12	**9**	0,12	0,12	**16**	0,12	0,25	**23**	0,12	1,12	**30**	0,25	1,87	**37**	0,12	1,75	**44**	0,12	1,75
3	0	0,12	**10**	0,12	0,12	**17**	0	0,37	**24**	0,12	0,75	31	0,37	1,37	**38**	1	1,12	**45**	1	1,12
4	0,12	0,12	**11**	0	0	**18**	0	0,12	**25**	0,37	0,25	**32**	1,37	0,12	**39**	2	0	**46**	2	0

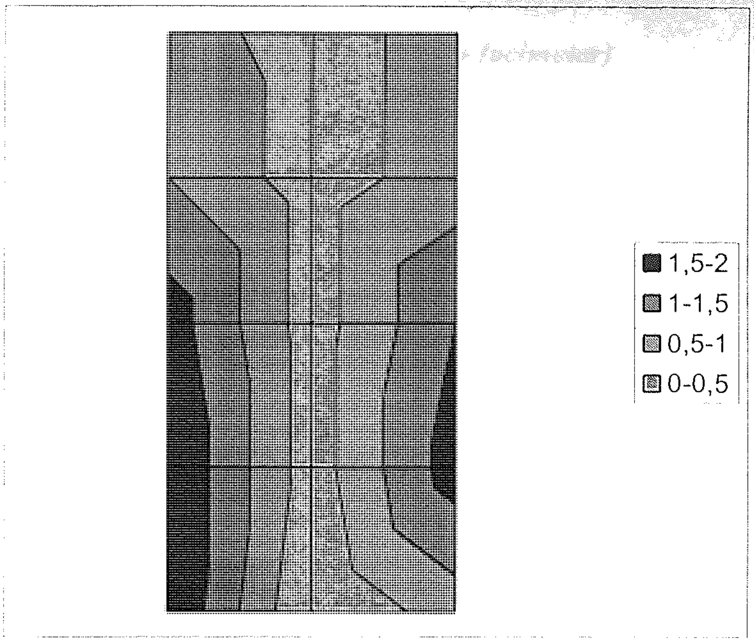
5	0	0,12	**12**	0,25	0	**19**	0	0,5	**26**	0	1	**33**	0,5	1,25	**40**	0,87	1,12	**47**	0,87	1,12
6	0,12	0,12	**13**	0,25	0	**20**	0,12	0,62	**27**	0,12	1,37	**34**	0,12	1,75	**41**	0,12	1,62	**48**	0,12	1,62
7	0,12	0,12	**14**	0,25	0,12	**21**	0,25	0,62	**28**	0,12	1,37	**35**	0,12	1,75	**42**	0,12	1,62	**49**	0,12	1,62

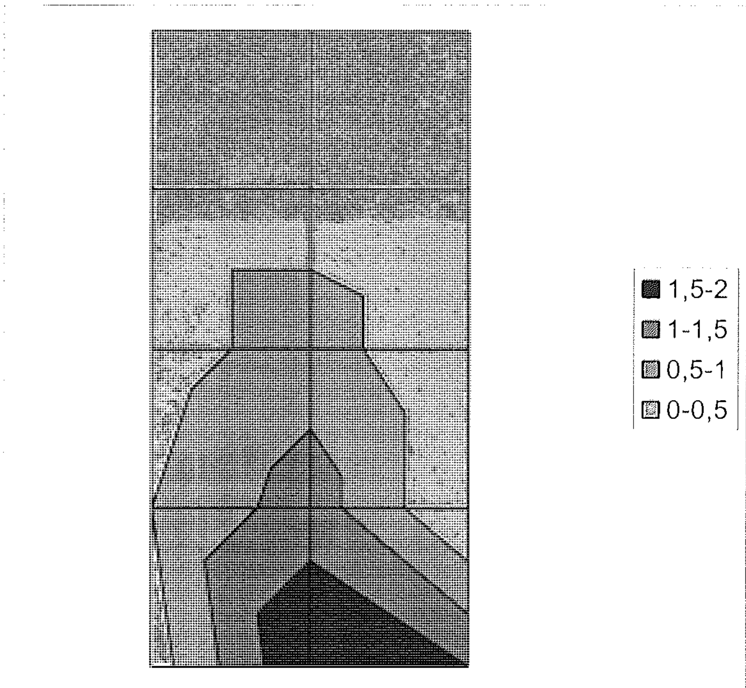




Hoya Summit Pro (Interferometer)

Plano	Add 2.00 Sph	Summit Cyl	Pro	Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
9	0,25	0,75	**16**	0,25	1	**23**	0,25	1,75	**30**	0,5	2	**37**	0,25	2
11	0	0,25	**18**	0,25	0,25	**25**	0,75	0,25	**32**	1,25	0,25	**39**	2	0
13	0	0,75	**20**	0	0,75	**27**	0	1,5	**34**	0	1,75	**41**	1,5	0,75

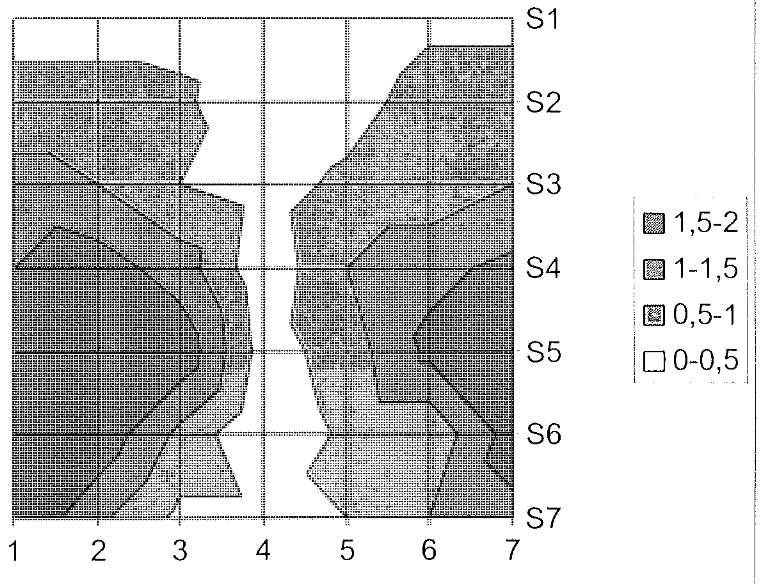

1,5-2
1-1,5
0,5-1
0-0,5

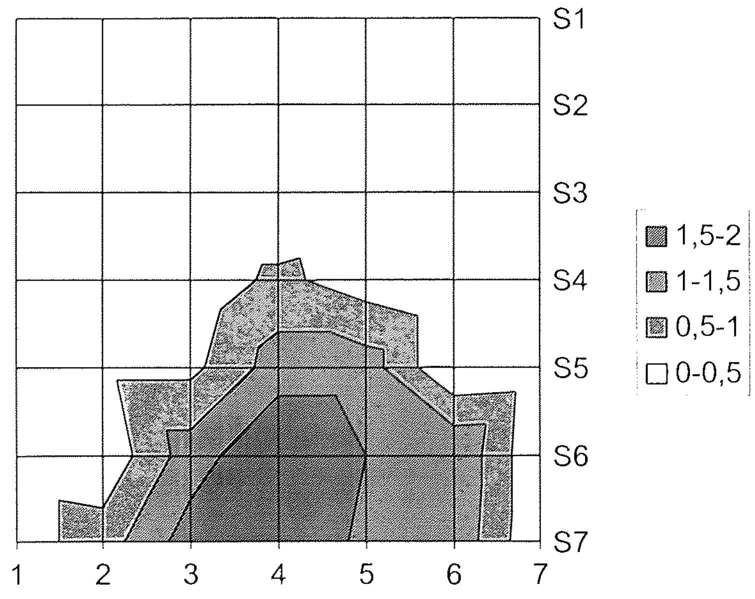

1,5-2
1-1,5
0,5-1
0-0,5

Hoya Summit Pro (Auto-focimeter)

Plano/Add 2.00

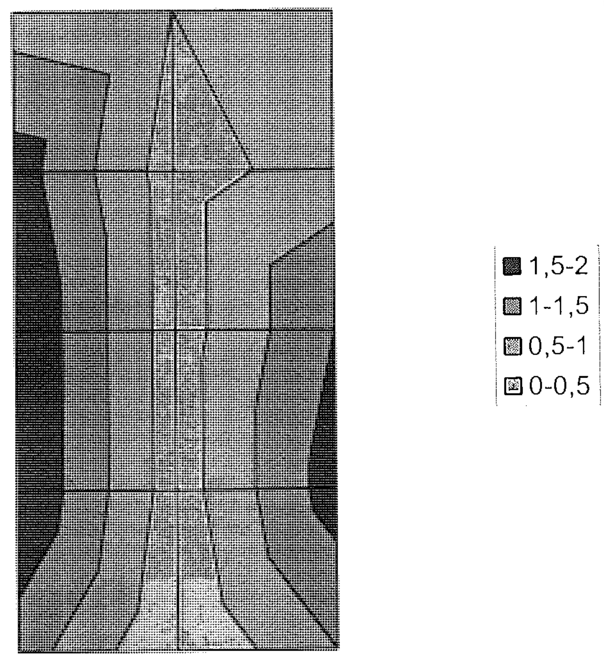
	Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
1	0,25	0,37	**8**	0,12	0,62	**15**	0,12	1,25	**22**	0,25	1,5	**29**	0,5	2	**36**	0,25	2	**43**	0,25	2
2	0,25	0,37	**9**	0,12	0,62	**16**	0,12	1	**23**	0,25	1,75	**30**	0,37	1,87	**37**	0,12	1,87	**44**	0,75	1,12
3	0,25	0,25	**10**	0	0,62	**17**	0	0,5	**24**	0,12	1,25	**31**	0,37	1,87	**38**	1,25	0,87	**45**	1,75	0,37
4	0,25	0,12	**11**	0	0	**18**	0	0,25	**25**	0,62	0,12	**32**	1,25	0,25	**39**	2	0	**46**	2	0,37
5	0,25	0	**12**	0,12	0,25	**19**	0,12	0,62	**26**	0,25	1	**33**	1,25	0,75	**40**	1,5	0,62	**47**	1,37	0,5
6	0,25	0,37	**13**	0	0,75	**20**	0	0,62	**27**	0	1,37	**34**	0	1,62	**41**	1,5	0,62	**48**	1,37	1
7	0,25	0,37	**14**	0	0,75	**21**	0,12	1	**28**	0	1,62	**35**	0,12	1,87	**42**	0	1,75	**49**	0	1,37

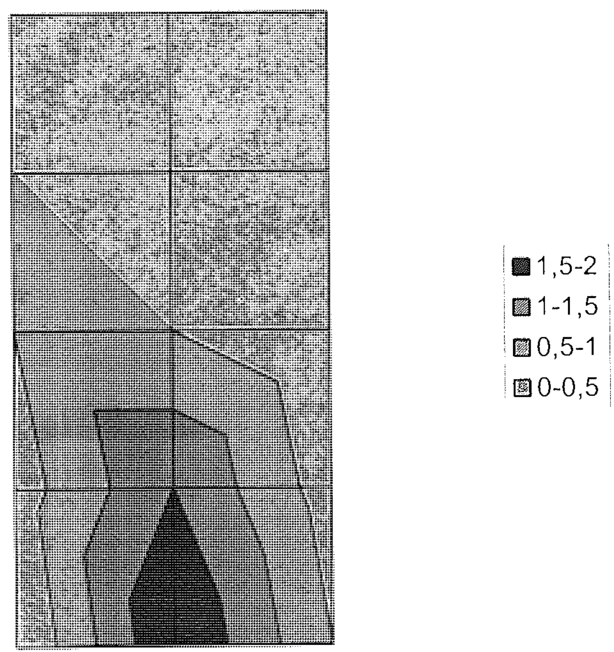




Nikon Presio (Interferometer)

Plano	Add 2.00 Sph	Presio Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
9	0,25	0,75	**16**	0,5	1,75	**23**	0,5	2	**30**	0,25	2	**37**	0	1,25
11	0,25	0,5	**18**	0,25	0,25	**25**	0,5	0,25	**32**	1,5	0,25	**39**	2	0
13	0,25	0,75	**20**	0,25	0,75	**27**	0	1,5	**34**	0,25	1,75	**41**	0,5	1

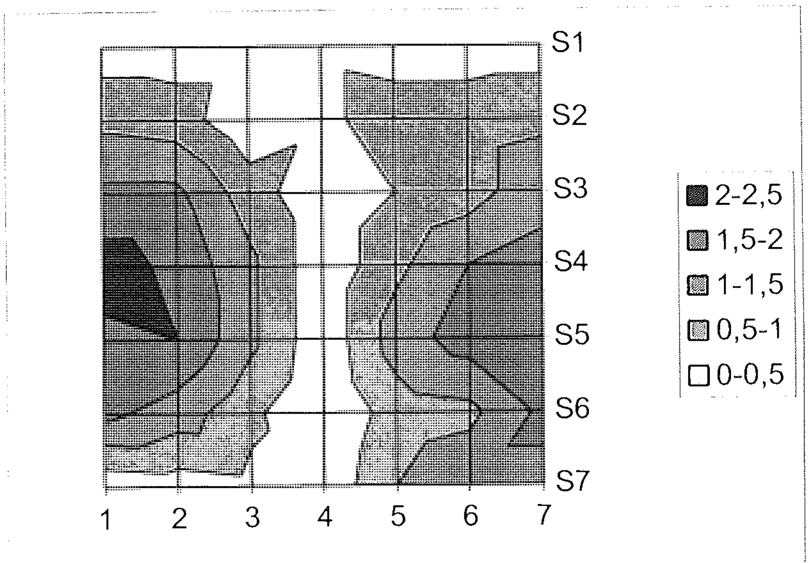


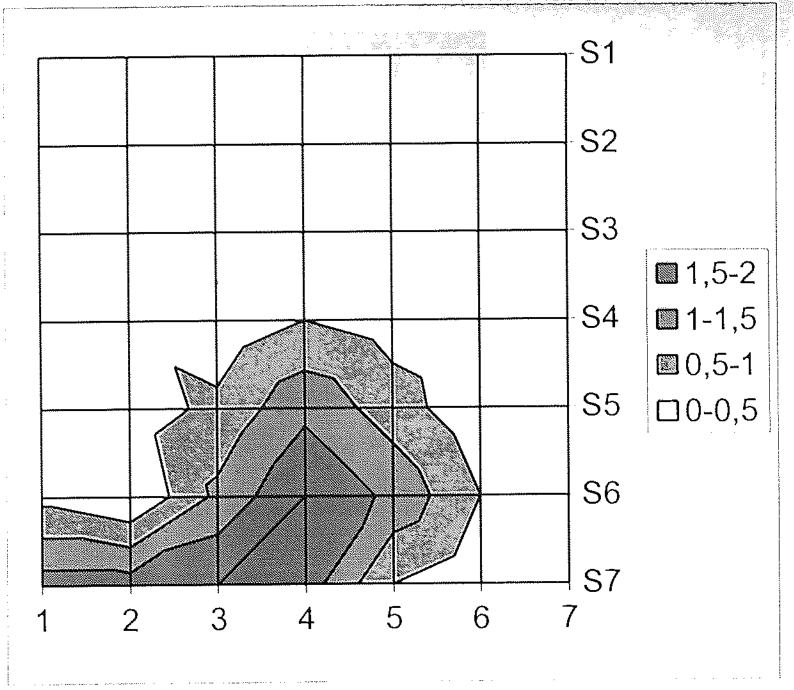


Nikon Presio (Auto-focimeter)

Plano/Add 2.00

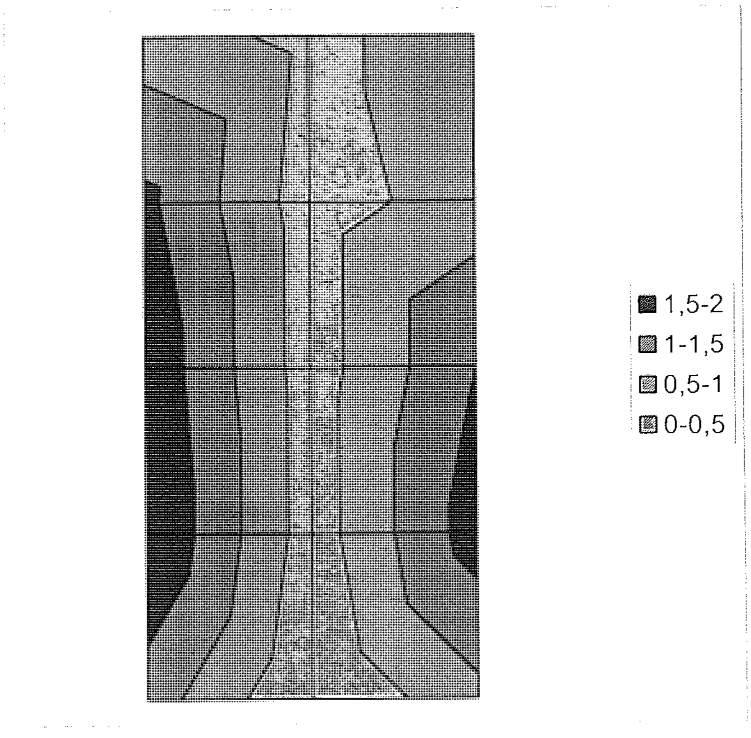
	Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
1	0,37	0,25	**8**	0,12	0,87	**15**	0,37	1,62	**22**	0,5	2,25	**29**	0,5	1,87	**36**	0,37	1,62	**43**	1,75	0,12
2	0,25	0,25	**9**	0,12	0,75	**16**	0,37	1,62	**23**	0,37	1,87	**30**	0,25	2	**37**	0	1,25	**44**	1,75	0,25
3	0,25	0,25	**10**	0,12	0,12	**17**	0	0,75	**24**	0,12	1,12	**31**	0,62	1,12	**38**	1,12	0,62	**45**	2	0,37
4	0,25	0,37	**11**	0	0,37	**18**	0,12	0,12	**25**	0,5	0,12	**32**	1,37	0,12	**39**	2	0	**46**	1,75	0,12
5	0,25	0,25	**12**	0	0,75	**19**	0	0,5	**26**	0,25	0,87	**33**	0,75	1,25	**40**	1,37	0,75	**47**	0,5	1
6	0,25	0,25	**13**	0,12	0,75	**20**	0,12	0,75	**27**	0	1,5	**34**	0,12	1,75	**41**	0,5	0,87	**48**	0,12	1,37
7	0,25	0,25	**14**	0,12	0,87	**21**	0,12	1,37	**28**	0,12	1,62	**35**	0,12	1,75	**42**	0,25	1,62	**49**	0,12	1,37

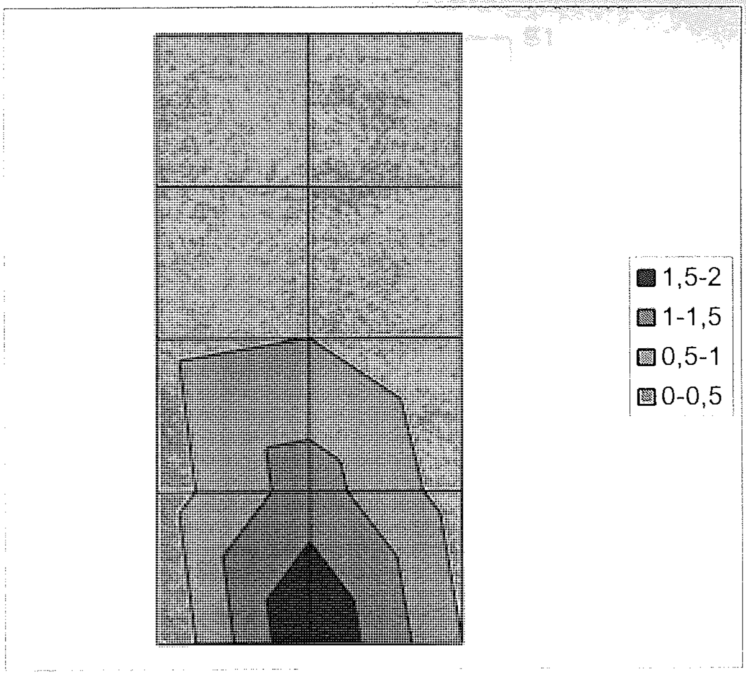




Rodenstock Progressive S (Interferometer)

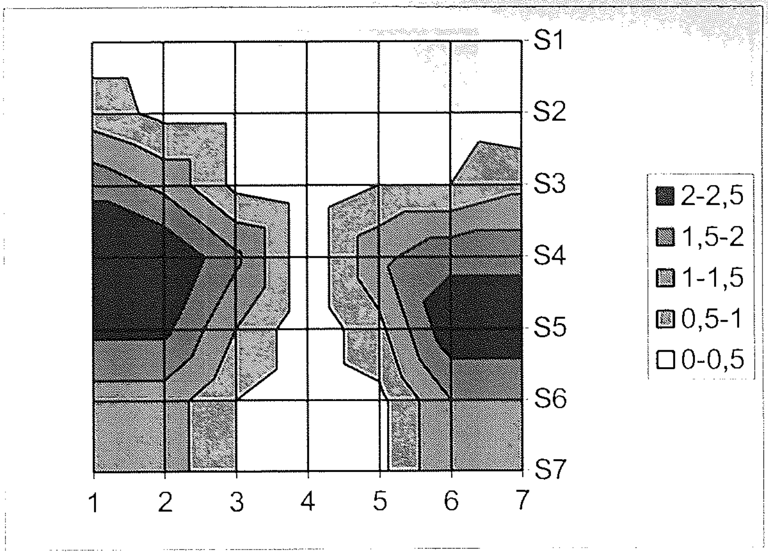
Plano	Add 2.00 Sph	Progressive S Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
9	0,25	0,75	**16**	0,37	1,62	**23**	0,37	1,87	**30**	0,25	2	37	0	1,25
11	0,25	0,37	**18**	0,25	0,25	**25**	0,5	0,25	**32**	1,25	0,25	**39**	2	0
13	0,25	0,75	**20**	0,25	0,75	27	0	1,5	**34**	0,25	1,75	**41**	0,5	0,87

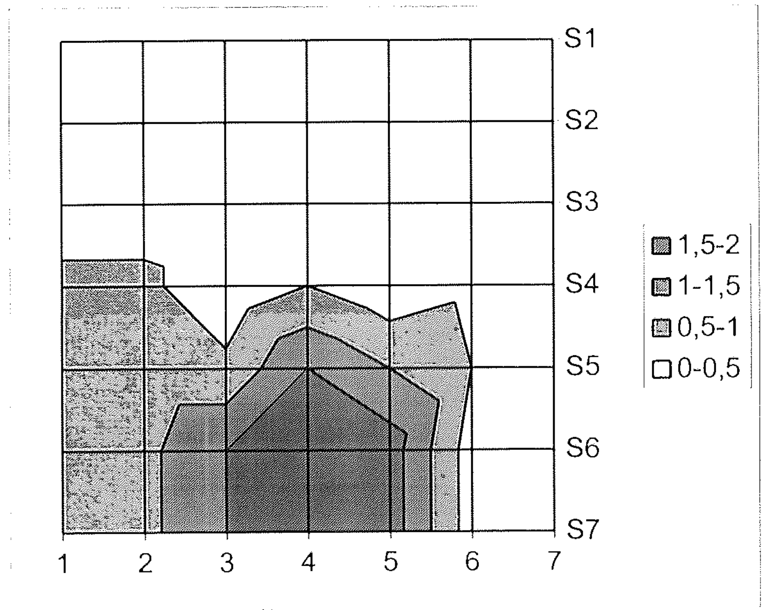




Rodenstock Progressive S (Auto-focimeter)

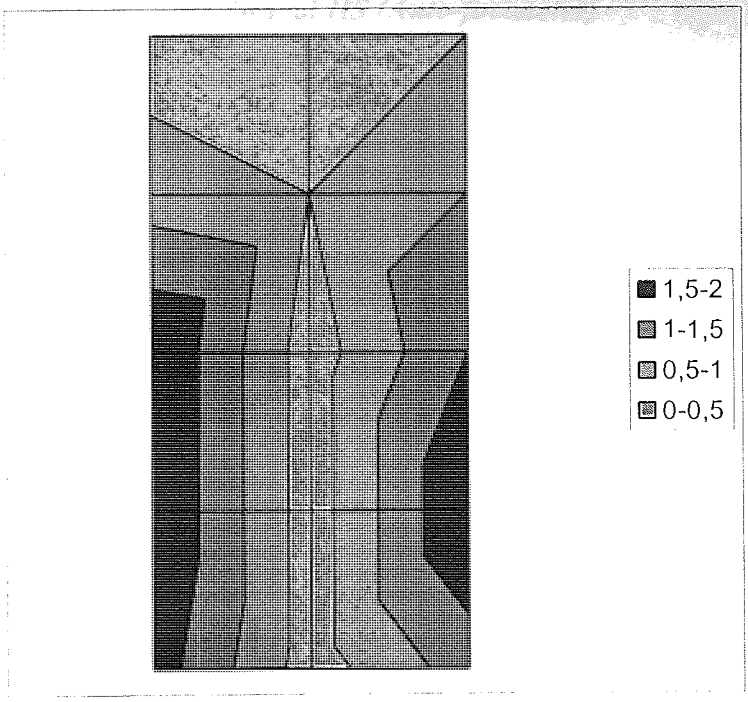
	plano	Add 2.00																			
	Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
1	0	0,25	**8**	0	0,75	**15**	0,25	1,87	**22**	0,62	2,5	**29**	0,62	2,12	**36**	0,87	1,25	**43**	0,87	1,25
2	0	0,25	**9**	0,12	0,37	**16**	0,25	1,37	**23**	0,62	2,5	**30**	0,62	2,12	**37**	0,87	1,25	**44**	0,87	1,25
3	0	0,12	**10**	0,12	0,37	**17**	0,12	0,37	**24**	0,12	1,62	**31**	0,62	1	**38**	1,5	0,5	**45**	1,5	0,5
4	0	0,37	**11**	0,12	0	**18**	0	0,12	**25**	0,5	0,12	**32**	1,5	0,12	**39**	2	0,12	**46**	2	0,12
5	0	0,12	**12**	0,12	0,25	**19**	0,12	0,5	**26**	0,12	1,37	**33**	1	0,87	**40**	1,75	0,37	**47**	1,75	0,37
6	0	0,37	**13**	0,12	0,25	**20**	0	0,5	**27**	0,37	1,87	**34**	0,5	2,37	**41**	0,25	1,5	**48**	0,25	1,5
7	0	0,37	**14**	0,12	0,12	**21**	0	0,87	**28**	0,37	1,87	**35**	0,5	2,37	**42**	0,25	1,5	**49**	0,25	1,5

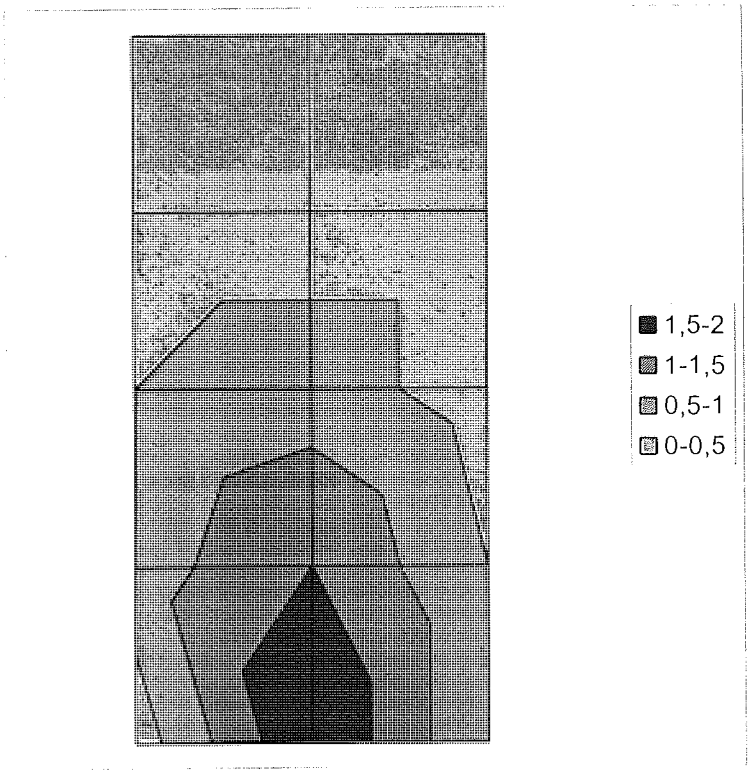




Zeiss Gradal HS (Interferometer)

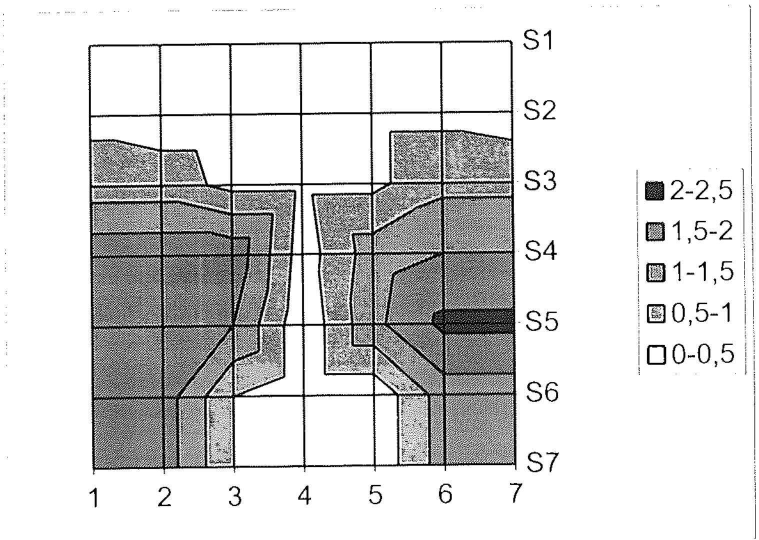
plano	Add 2.00	Gradal HS												
	Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
9	0,25	0,25	**16**	0,25	0,75	**23**	0,5	2	**30**	0,75	2	**37**	0,25	1,75
11	0,25	0	**18**	0,25	0,5	**25**	0,75	0,25	**32**	1,5	0,25	**39**	2	0,25
13	0,25	0,5	**20**	0,25	1	**27**	0,25	1,5	**34**	0,5	2	**41**	0,5	1,25

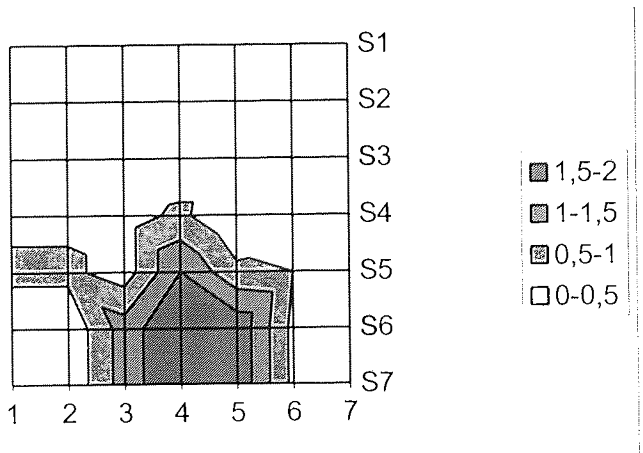

1,5-2
1-1,5
0,5-1
0-0,5


1,5-2
1-1,5
0,5-1
0-0,5

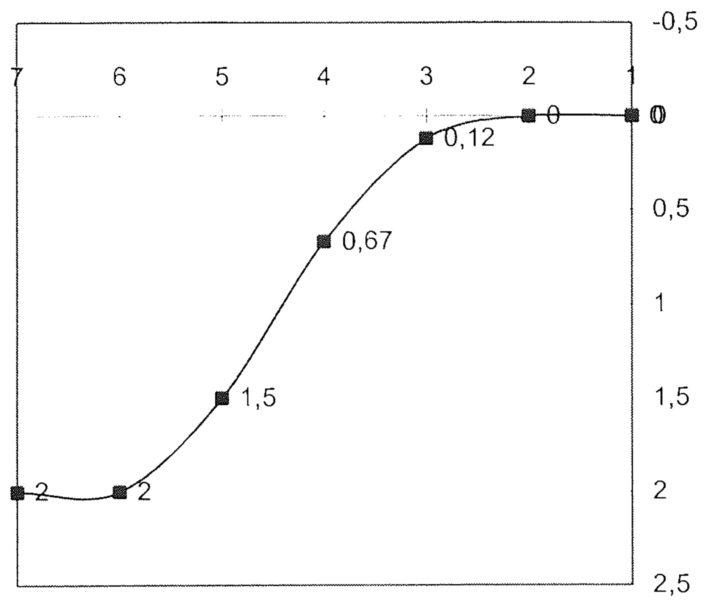
Zeiss Gradal HS (Auto-focimeter)

	plano Sph	Add 2.00 Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl		Sph	Cyl
1	0	0,37	**8**	0,25	0,37	**15**	0,25	0,75	**22**	0,37	1,87	**29**	0,62	1,87	**36**	0,12	1,75	**43**	0,12	1,75
2	0	0,37	**9**	0,25	0,25	**16**	0,25	0,75	**23**	0,37	1,87	**30**	0,62	1,87	**37**	0,12	1,75	**44**	0,12	1,75
3	0,12	0,25	**10**	0,25	0,25	**17**	0	0,37	**24**	0,25	1,87	**31**	0,25	1,5	**38**	1,25	0,5	**45**	1,25	0,5
4	0,12	0,12	**11**	0,12	0	**18**	0,12	0,37	**25**	0,62	0,25	**32**	1,5	0,12	**39**	2	0,12	**46**	2	0,12
5	0,12	0,12	**12**	0,12	0,37	**19**	0,12	0,37	**26**	0	1,25	**33**	0,62	1,37	**40**	1,87	0,12	**47**	1,87	0,12
6	0,12	0,12	**13**	0,12	0,37	**20**	0,25	0,87	**27**	0,12	1,5	**34**	0,5	2,12	**41**	0,37	1,25	**48**	0,37	1,25
7	0,12	0,12	**14**	0,12	0,25	**21**	0,25	0,87	**28**	0,12	1,5	**35**	0,5	2,12	**42**	0,37	1,25	**49**	0,37	1,25

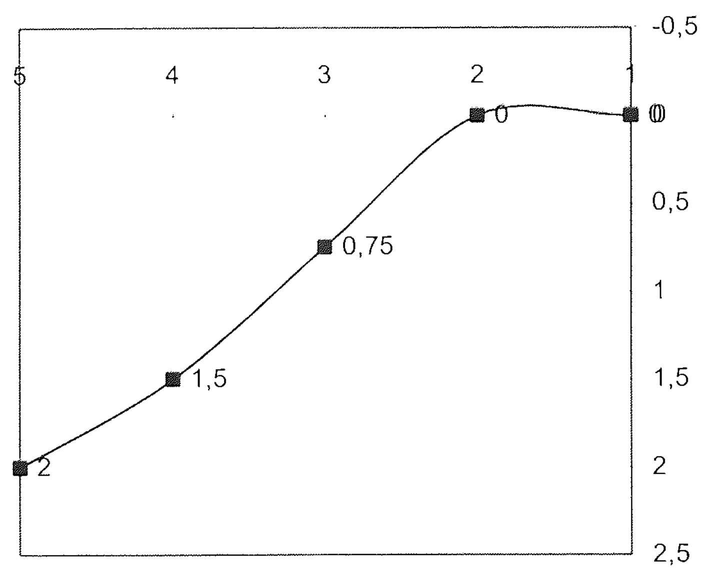




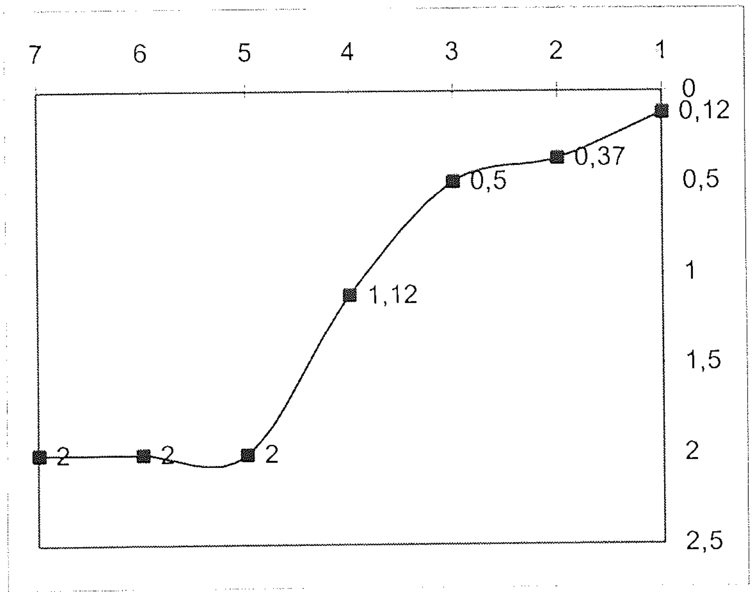
The above figures show the power and the unwanted astigmatism distribution through the surface of each progressive addition ophthalmic lens measured. With interferometer 15 points were measured while with the Auto-focimeter 49.



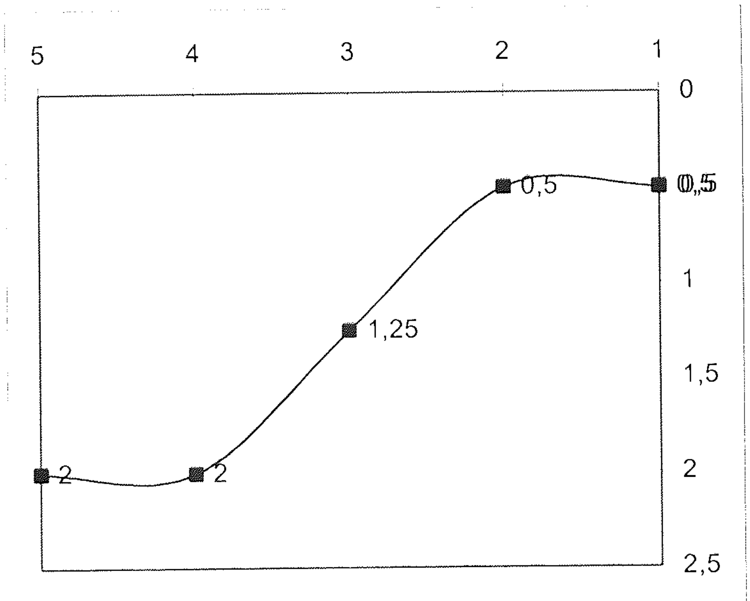
AOptical Pro Add : 2.00 (Auto-focimeter)



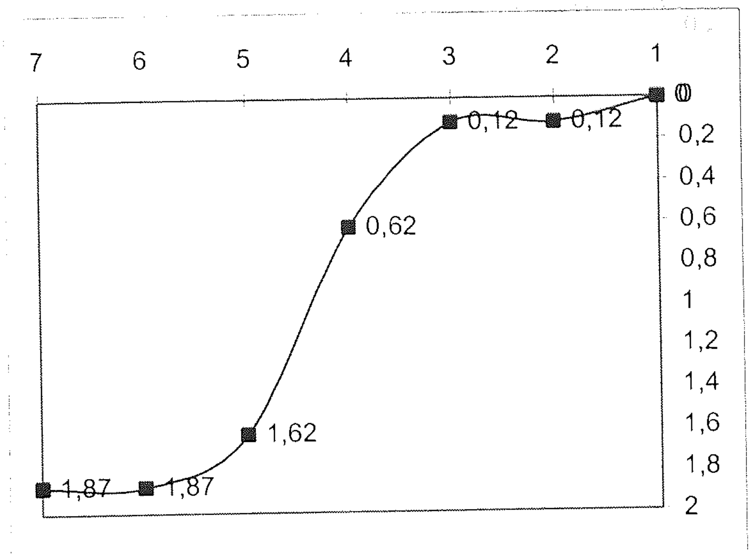
AOptical Pro Add : 2.00 (Interferometer)



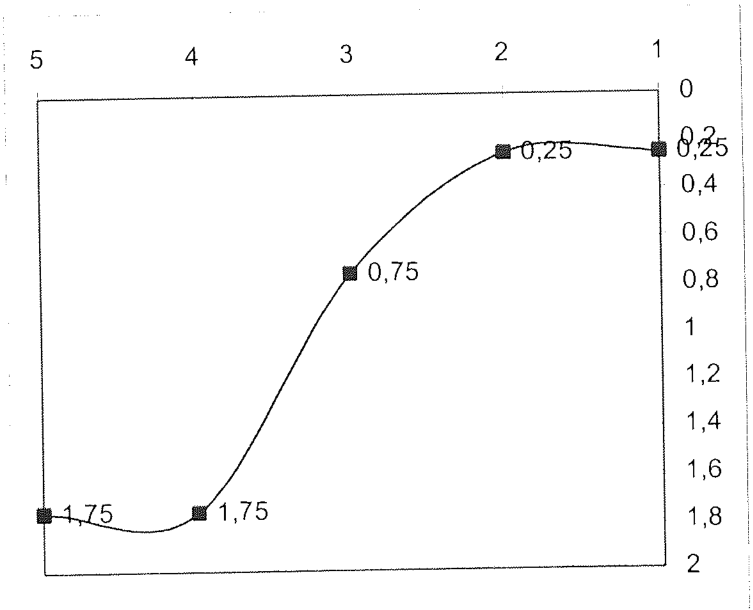
AOptical Compact Add : 2.00 (Auto-focimeter)



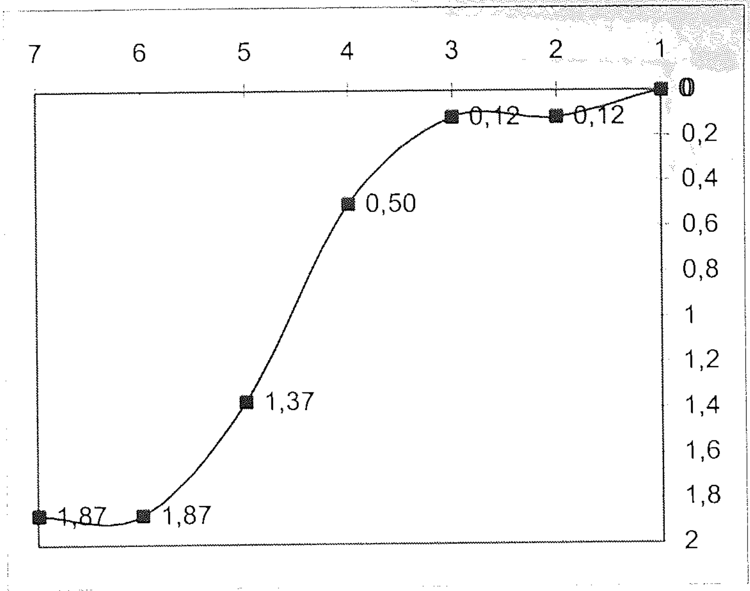
AOptical Compact Add : 2.00 (Interferometer)



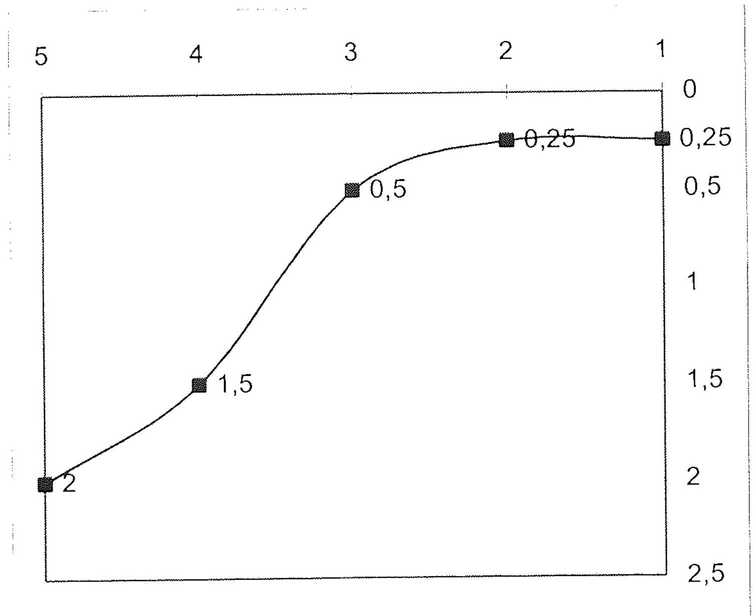
Essilor Varilux Comfort Add: 2.00 (Auto-focimeter)



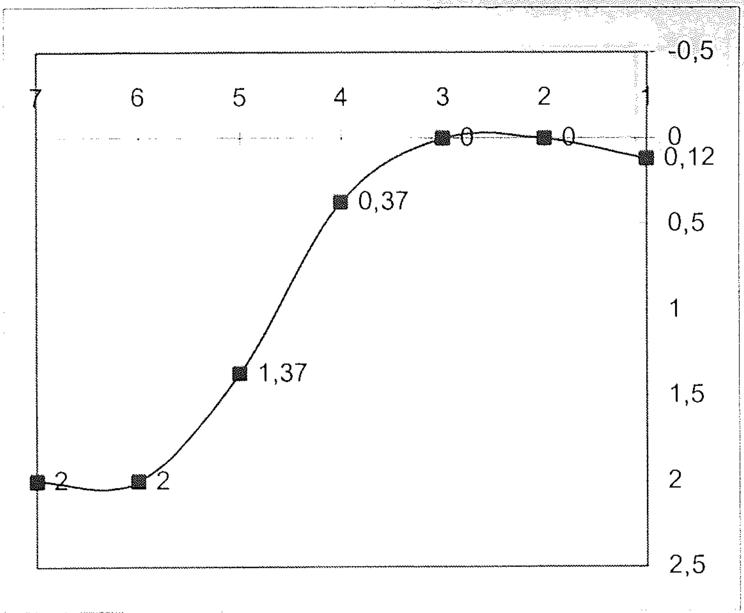
Essilor Varilux Comfort Add: 2.00 (Interferometer)



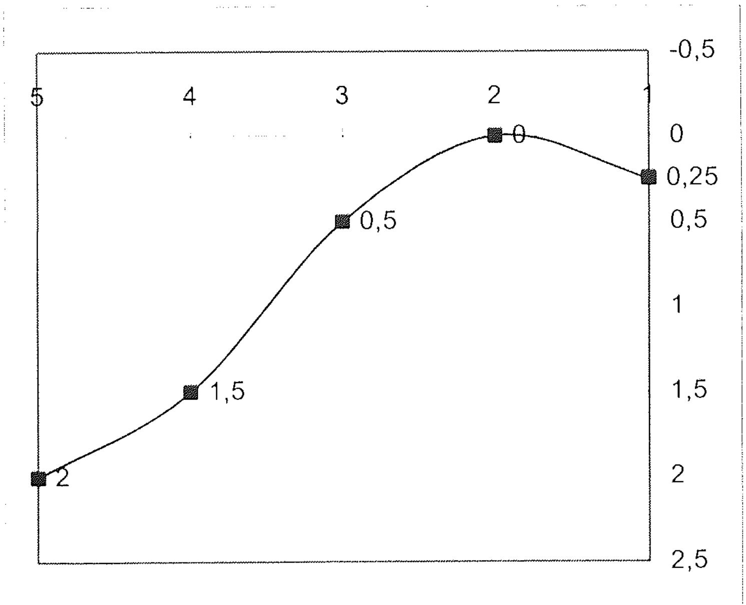
Essilor Varilux Panamic Add: 2.00(Auto-focimeter)



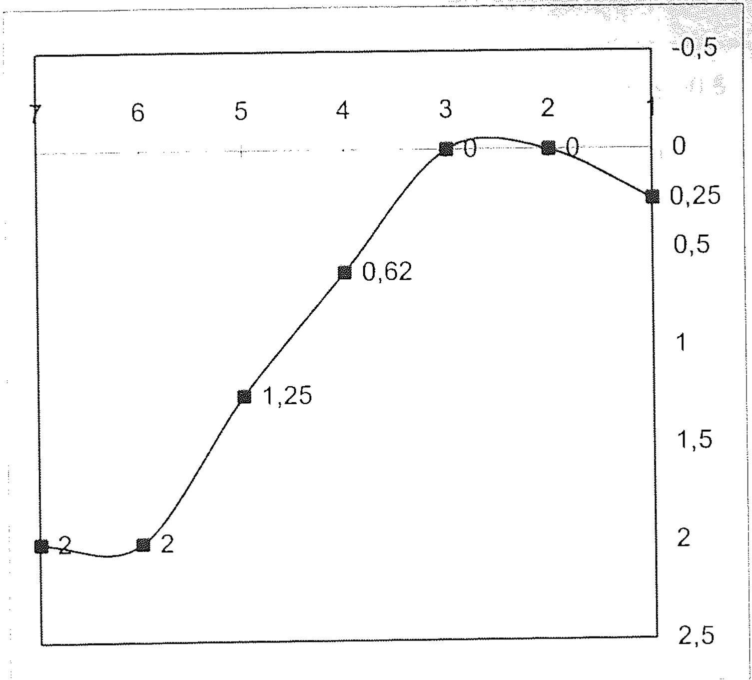
Essilor Varilux Panamic Add:2 .00 (Interferometer)



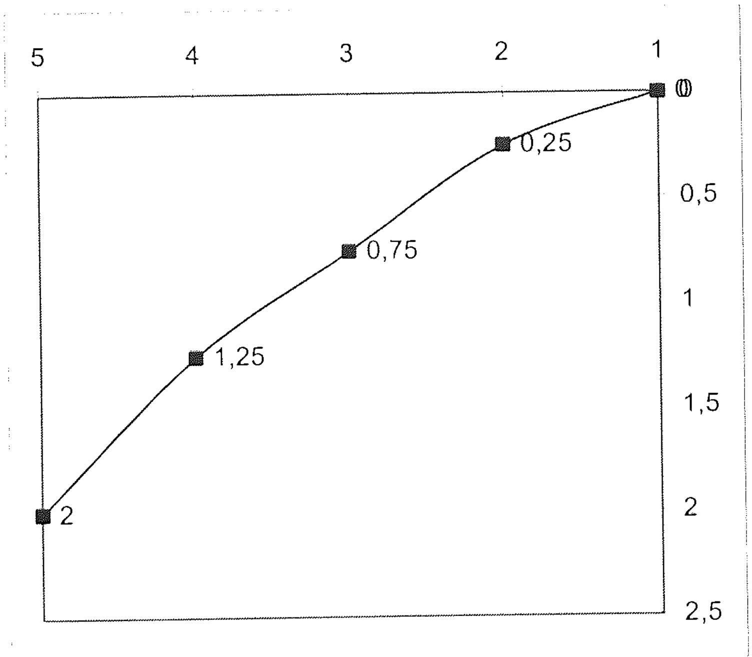
Hoya GP Add: 2.00 (Auto-focimeter)



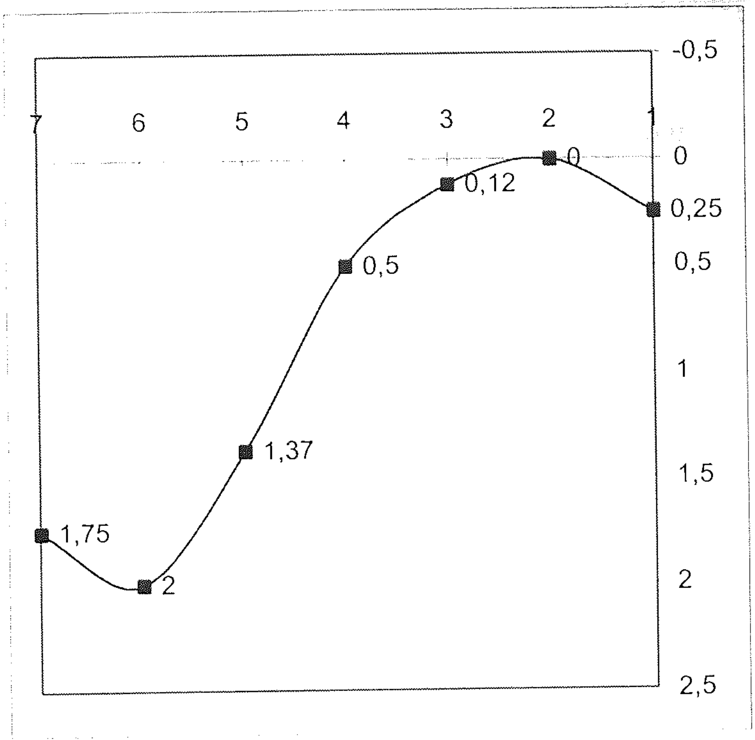
Hoya GP Add: 2.00 (Interferometer)



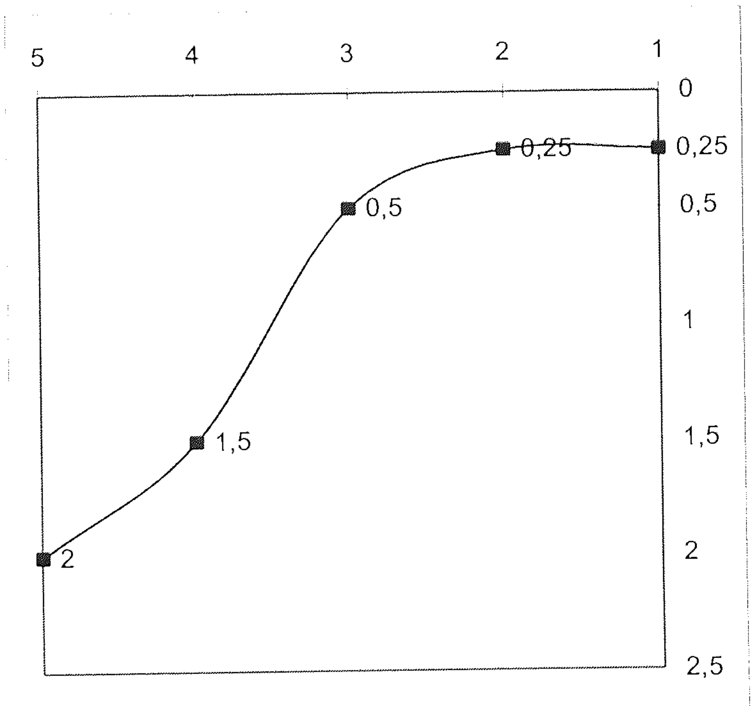
Hoya Summit Pro Add: 2.00(Auto-focimeter)



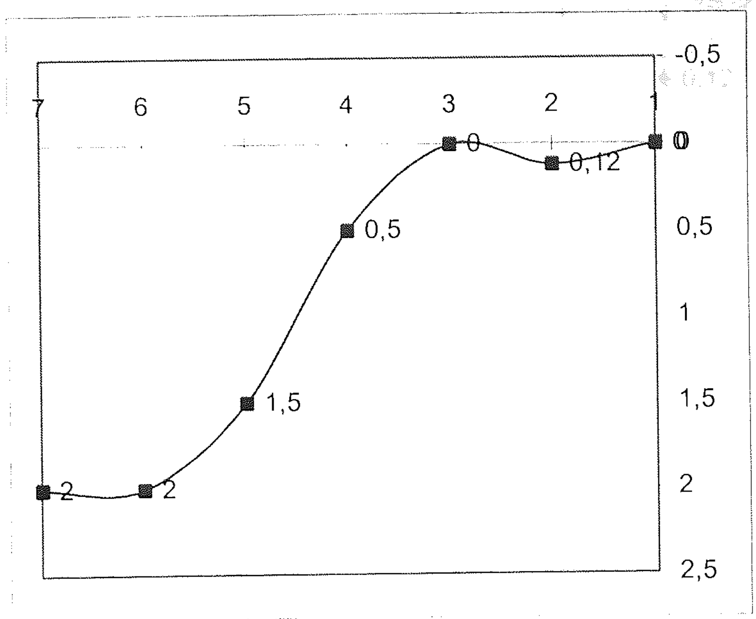
Hoya Summit Pro Add: 2.00 (Interferometer)



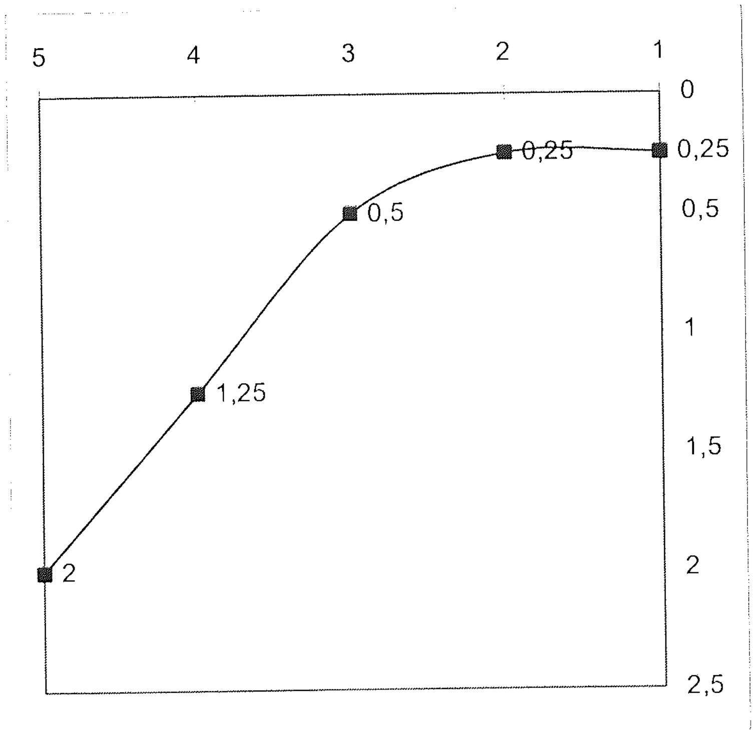
Nikon Presio Add: 2.00 (Auto-focimeter)



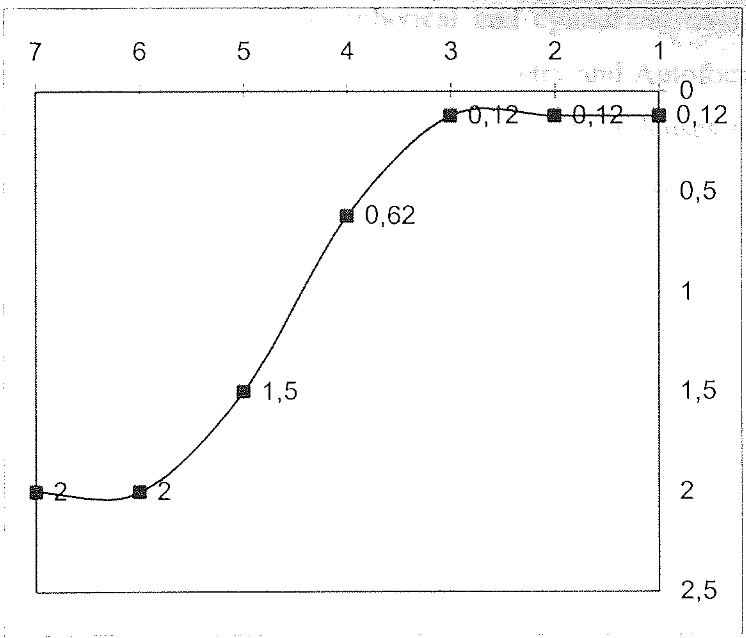
Nikon Presio Add: 2.00 (Interferometer)



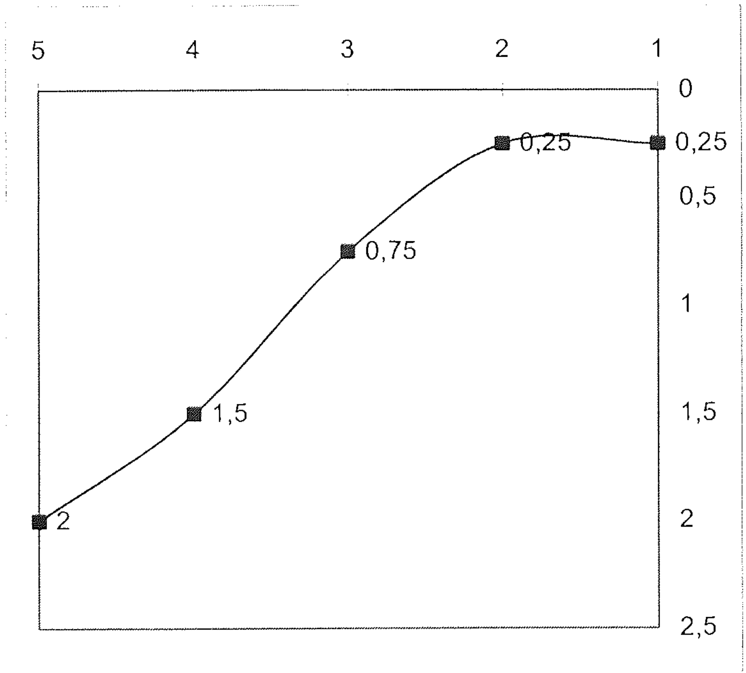
Rodenstock Progressive S Add: 2.00(Auto-focimeter)



Rodenstock Progressive S Add: 2.00 (Interferometer)



Zeiss Gradal HS Add: 2.00(Auto-focimeter)



Zeiss Gradal HS Add: 2.00 (Interferometer)

The above figures show the power progression through the corridor of each ophthalmic lens measured. Point (1) for the results for the interferometer technique and point (3) for the results for the Auto-focimeter correspond to the cross and point (5) for the results for the interferometer technique and point (6) for the results for the Auto-focimeter the beginning of the near addition area.

According now to the plotting of the spherical and cylindrical component of the progressive addition lenses measured with interferometry and Autofocimeter we can compare the lens designs by checking the plotting for all the lenses measured with plano distance and near addition of +2.00DS

VARILUX COMFORT

(Highest value of astigmatism 2.00 dpt. Interferometric – 2.37dpt. Autofocimeter)

It is observed the presence of high astigmatic aberrations (one of the highest concerning the other lenses tested). The umbilical line is not actually free of astigmatic components but it does not exit 0.37 Dcyl , which is acceptable for the eye.

In the first 15 mm only 33% of the addition is reached while at 20 mm 87% of the addition is reached.

VARILUX PANAMIC

(Highest value of astigmatism 1.75dpt. for both methods)

The umbilical line, as with Comfort, is not actually free of astigmatic components but it does not exit 0.37 Dcyl , which is acceptable for the eye.

Nevertheless, the highest value of astigmatism is lower in comparison with **Varilux Comfort.** In the first 15 mm only 26% of the addition is reached while at 20 mm 87% of the addition is reached.

Generally **Varilux Comfort** is suggested for patients having requirements for distant and near peripheral vision, where it has better behavior, and less in the intermediate zone. **Varilux Panamic** has an adequate width of intermediate channel and better vision in the peripheral regions of the progressive channel.

HOYA GP

(Highest value of astigmatism 2.00 dpt. Interferometric - 1.87dpt. Autofocimeter)

We observe almost zero values in points 1 up to 7 . The highest value of astigmatism of lens HOYA is 1,87dpt, which is satisfactory compared with the other lenses In the distant region this particular lens presents very low values of astigmatism. Therefore such a lens is proposed to patients that uses their progressive spectacles mainly for distant vision. The umbilical line is not actually free of astigmatism but it does not exit 0.25 Dcyl , which is acceptable for the eye, and is a bit lower than Comfort and Panamic. In the first 15 mm only 18% of the addition is reached while at 20 mm, 68% of the addition is reached.

HOYA Summit Pro

(Highest value of astigmatism 2.00dpt. for both methods)

The distance vision area suffers from astigmatic aberration which goes up to 0.75 Dcyl. The umbilical line is not actually free of astigmatic components but it does not exceed 0.12 Dcyl , which is acceptable for the eye, and one of the lowest values found in the lenses measured. In the first 15 mm only 31% of the addition is reached while at 20 mm 62% of the addition is reached.

RODENSTOCK PROGRESSIVE S

(Highest value of astigmatism 2.00 dpt. Interferometric – 2.50 dpt. Autofocimeter)

Note the presence of high values of astigmatism, the highest measured in this group of lenses. The umbilical line is not actually free of astigmatic components but it does not exceed 0.12 Dcyl , which is acceptable for the eye, and lower than the previous lenses tested. In the first 15 mm only 25% of the addition is reached while at 20 mm 75% of the addition is reached. Both Hoya GP and Rodenstock progressive S reach exactly the nominal power of addition 2.00Ds, compared with Varilux, which reaches 1.87 Ds.

sZeiss Gradal HS

(Highest value of astigmatism 2.00 dpt. Interferometric – 2.12 dpt. Autofocimeter)

The umbilical line is not actually free of astigmatic components but it does not exceed 0.12 Dcyl , which is acceptable for the eye, and the equal lowest (the Rodenstock and AO lenses have the same value) when compared with the other lenses tested. In the first 15 mm only 25% of the addition is reached while at 20 mm 75% of the addition is reached. The whole design resembles the one of Rodenstock.

AOptical PRO

(Highest value of astigmatism 2.00 dpt. Interferometric - 1.87dpt. Autofocimeter)

The distance vision area suffers from astigmatic aberrations which do not exceed 0.37 Dcyl. The umbilical line is not actually free of astigmatic components but it does not exceed 0.12 Dcyl , which is acceptable to the eye, and equal lowest with the Rodenstock and Zeiss lenses. In the first 15 mm only 33% of the addition is reached while at 20 mm 75% of the addition is reached.

AOptical Compact

(Highest value of astigmatism 2.00 dpt. Interferometric - 1.87dpt. Autofocimeter)

The distance vision area suffers from astigmatic aberration which does not exceed 0.37 Dcyl. The umbilical line is not actually free of astigmatic components but it does not exceed 0.12 Dcyl , which is acceptable for the eye, and the lowest (the Rodenstock, AO PRO and Zeiss lenses have the same). In the first 15 mm only 55% of the addition is reached while at 20 mm 100% of the addition is reached. This lens is a different design compared with the previous lenses. The addition as it can be seen is reached much earlier than the other lenses, which makes such a progressive addition lens suitable for small frames.

Nikon Presio

(Highest value of astigmatism 2.00 dpt. Interferometric - 1.87dpt. Autofocimeter)

The distance vision area suffers from astigmatic aberration which goes up to 0.87 Dcyl. The umbilical line is not actually free of astigmatism, but this does not exceed 0.12 Dcyl , which is acceptable for the eye. In the first 15 mm only 25% of the addition is reached while at 20 mm 69% of the addition is reached.