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Effects of chromatic light interventions and wavelengths on ocular biometry in human myopia: A systematic review and meta-analysis

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ABSTRACT

Studies highlight the use of different wavelengths of light as emerging interventions to slow myopia progression in children. This review evaluates the effects of different wavelengths of chromatic light interventions on ocular biometry in humans. A literature search of MEDLINE, CINAHL, Scopus, ProQuest Central, Web of Science, and trial registries identified thirty-seven studies examining the effects of either long-term (4 weeks- 24 months) or short-term (between 10–120 min and $\leq$ 4 weeks) monochromatic light exposure. A random-effects model was used to calculate the weighted mean difference (WMD) and 95 % confidence intervals (CI) in spherical equivalent refraction (SER), axial length (AL) and subfoveal choroidal thickness (ChT). In studies examining long-term exposure to both long- and short-wavelength light, significant changes in AL, SER, and ChT were observed primarily with long-wavelength red light used in repeated low-level red light (RLRL) therapy. RLRL resulted in a significant reduction in AL and SER, and an increase in subfoveal ChT compared to a control group wearing single vision spectacles (SVS) at both 6 and 12 months (WMD at 6 and 12 months, AL:0.24 and –0.36 mm; SER: 0.31 and 0.77 D; ChT: +32.12 and +31.78 μm). Exposure to short-wavelength (blue and/or violet light) resulted in only a modest change in AL and myopia progression in children [mean change (95 % CI) at 12 months, AL:0.04 mm (–0.15 to 0.07); SER: 0.04 D (–0.16 to 0.24)]. Short-term exposure to both long- and short-wavelengths on ocular biometry in young adults showed equivocal results. LED-based blue light (454–456 nm) induced choroidal thickening and a reduction in AL, whereas red light produced the opposite effects. In conclusion, longer-term exposure to RLRL and violet light can slow myopia progression in children, with RLRL showing a stronger effect. Short-term exposure to different wavelengths offers insights for developing newer light-based myopia therapies.

1. Introduction

Myopia or near-sightedness is a refractive error primarily caused by a mismatch between the optical components (i.e. the cornea and the crystalline lens) and axial length (AL) of the eye, where parallel light rays entering the eye focus in front of the retina, resulting in blurred distance vision [1,2]. Axial myopia, the most common form of myopia, is characterised by an excessive axial elongation of the eyeball, resulting in thinning of the posterior segment layers, including the retina, choroid and sclera [3]. Myopia presents a significant global health issue, with 4.8 billion people estimated to be affected by 2050 [4], and imposes substantial socioeconomic burden [5]. Early onset of myopia in children increases the risk of faster disease progression and a higher likelihood of developing high myopia and its related complications [6,7]. Among various risk factors for myopia, near work and time outdoors are the most extensively investigated [8].

Several cross-sectional and longitudinal studies have found that increased outdoor time is associated with reduced myopia onset with [9]. In addition to optical [10] and neurochemical factors (such as dopamine release) [11], one important factor could be the spectral

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composition of outdoor versus indoor light in modulating ocular growth and myopia in children [12]. In support of this, animal studies have shown varying effects of wavelength and spectral composition of light on ocular growth and experimental myopia in animal models [12].

Experimental models suggested that the process of emmetropisation (the systematic and coordinated eye growth process) uses chromatic cues from longitudinal chromatic aberration (LCA) to encode the sign of defocus and to regulate eye growth [13]. LCA is an optical mechanism, that causes shorter wavelength blue light to refract more than longer wavelength red light, such that the blue light focuses in front of the retina and the red light behind the retina. As a result, the eye's overall refraction changes inversely with respect to wavelength, making the eye more hyperopic (less myopic) for longer wavelength of light [14]. Recently, Gawne and Norton proposed that emmetropisation compares the image contrast produced by short versus long wavelength cones and makes compensatory changes in ocular growth, guiding the eye towards emmetropia [15]. However, animals also emmetropise under narrowband lighting where LCA-cues for optical defocus are essentially absent, implying the involvement of wavelength specific defocus signals, in addition to chromatic signals from LCA, to guide ocular growth [16–18]. For instance, guinea pigs [19], fish [20,21], and chicks [22] develop myopia when raised under middle or long-wavelength (green or red) light and hyperopia under short-wavelength (violet and blue) light [23–25]. Conversely, rhesus monkeys [26] and tree shrew [27,28] exposed to long-wavelength exhibit reduced axial growth and choroidal thickening, and less myopic refraction.

Emerging studies highlight the use of different wavelengths of light as potential interventions, particularly through the use of RLRL therapy [29] and violet light exposure (360–400 nm) [30–32], to slow myopia progression in children. The effect of RLRL and violet transmitting eyewear has been evaluated in clinical trials, with RLRL showing particularly high efficacy in controlling axial growth and myopia progression in children [33]. Several recent studies have also explored the short-term (60 – 120 min) effects of long- and short-wavelength light on ocular biometry in young adult humans with equivocal results [34–37].

Although recent systematic reviews have evaluated the efficacy of RLRL treatment [29,38], a limited number of reviews have directly and rigorously compared the efficacy of long-wavelength (RLRL therapy) and short-wavelength (violet light glasses) chromatic light interventions on myopia progression in children [39]. To date, no comprehensive review has synthesised the collective evidence regarding the short-and long-term effects of narrowband wavelengths on ocular biometry in humans. This review aims to provide a holistic and contemporary overview of the effects of chromatic light interventions and wavelengths on ocular biometry in human myopia, and more importantly how these chromatic interventions may serve as novel strategies for myopia management. Here, we have evaluated the effectiveness of longer-term chromatic light interventions (RLRL therapy and violet light glasses), with exposure durations ranging from four weeks to 24 months, on myopia progression, AL and choroidal thickness (ChT) in children. Additionally, the review examines the impact of short-term exposure (ranging from 10–120 min up to $\leq$ four weeks) to different wavelengths on ocular biometry in human subjects. Finally, emerging light-based interventions are also discussed as potential future treatments for myopia.

2. Methodology

This review followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [40] and was prospectively registered on PROSPERO (CRD42024579559). The research question was structured using the PICO framework. The Population (P) included individuals with myopia, the Intervention (I) focused on long- and short-wavelength monochromatic lighting, the Comparison (C) for myopia interventions, such as RLRL, was made against single vision spectacles (SVS), and for short-term studies, the effect of light exposure was compared between myopic and emmetropic individuals, and the Outcome (O) assessed changes in spherical equivalent refraction (SER), AL and subfoveal ChT.

2.1. Search strategy

A comprehensive literature search was performed on January 4, 2025, using electronic databases (MEDLINE, CINAHL, Scopus, ProQuest Central, Web of Science), and trial registries (Cochrane Central Register of Controlled Trials, ANZCTR, and ClinicalTrials.gov) to identify relevant studies, without any restrictions on time of publication. The following search terms ["Myopia" OR "Myopes" OR "Myopic" OR "Near-sightedness" OR "Short-sightedness"] AND ["Narrowband wavelength" OR "Monochromatic light" OR "Red light" OR "Blue light" OR "Violet light" OR "Ultraviolet" OR "Short wavelength" OR "Medium wavelength" OR "Long wavelength"] AND ["Axial length" OR "Choroid" OR "Refraction"] were applied. The detailed search terms used for each database are detailed in the Supplementary file, Table 1. The search was restricted to studies involving human participants and full-text literature available in English.

2.2. Eligibility criteria

2.2.1. Long-term studies with exposure durations between four weeks and 24 months

Globally published studies examining the effects of chromatic light interventions on myopia progression and ocular biometry between four weeks and 24 months were deemed eligible if they met the following criteria: (1) randomised controlled trials (RCTs), prospective or retrospective case-control studies, observational cohort or cross-sectional studies; (2) children with myopia (SER of ≤ -0.50 D); (3) studies involving ocular exposure to monochromatic light or narrowband wavelengths (e.g., red, violet/ultraviolet, or blue); (4) studies that examined the effects of monochromatic lighting on at least one of the following outcome measures: AL change, change in SER, or ChT; (5) clinical trials with or without a control group, including those involving SVS or single-vision contact lenses.

RCTs evaluating the treatment effects of RLRL or other chromatic light therapies after 6 and/or 12 months of intervention in slowing myopia progression, reducing AL elongation, and preventing choroidal thinning were further included for meta-analysis. Light interventions involving full-spectrum or broadband lighting, or those used in conjunction with other myopia control interventions (such as atropine treatment, optical intervention, or surgical interventions like UV light for collagen cross-linking) were excluded.

2.2.2. Short-term studies with exposure durations between 10–120 min and $\leq$ four weeks

Studies that evaluated the effects of short-term exposure (between 10–120 min and $\leq$ four weeks) to monochromatic light or narrowband wavelengths on SER, AL or ChT in children and/or young adults were included. Previous studies have shown that ChT changes measured at least four weeks after the initiation of optical treatments may serve as a reliable predictor of long-term ocular growth [41,42]. Therefore, this review defined 'short-term' exposure as a duration of $\leq$ four weeks to guide the selection of relevant studies.

For both long and short-term studies, case reports, case series, methodological studies, reviews, conference papers, letters to the editor or commentaries, and articles without available full texts were excluded.

2.3. Study selection

Following the search, all identified citations were compiled and uploaded into EndNote (Clarivate Analytics, PA, USA), and duplicates removed. The titles and abstracts were screened by two independent reviewers (AH and RC) to assess their eligibility against the inclusion

criteria. Potentially relevant studies were retrieved in full, and their citation details were imported into the Covidence systematic review software (Veritas Health Innovation, Covidence, Melbourne, Australia). The reference lists of all eligible studies were manually searched to identify any additional studies of interest. The full texts of the selected studies were assessed in detail against the inclusion criteria by the same two independent reviewers. Reasons for excluding studies that did not meet the inclusion criteria were recorded and reported in Fig. 1. Disagreements between the reviewers at each stage of the selection process were resolved through discussion with a third reviewer (JE). The results of the search are presented as a PRISMA flow diagram (Fig. 1).

2.4. Data extraction for meta-analysis

Two independent reviewers (AH and JE) extracted data using an Excel (Microsoft corporate, USA) spreadsheet. The extracted information included specific details about the participants' demographics, study methods, interventions, primary outcomes (mean change in SER, AL and ChT), key findings and relevant contextual details. Means and standard deviations (SDs) were calculated for continuous variables; missing SDs were derived using alternative data available, such as confidence intervals, as previously described [43] When results were reported as medians with interquartile ranges, means and SDs were estimated using established methods [44]. Confidence intervals were calculated using a standard z-value (1.96) to ensure consistency in the pooled results [43]. This standardised approach supported meta-analysis and enabled comparison across studies despite variations in reported metrics. The compiled data is presented in Supplementary Table 1.

2.5. Quality assessment

The Risk of Bias in Non-Randomised Studies of Interventions (ROBINS-I) [45] and the Cochrane Risk of Bias (ROB 2) [46] tools were employed to assess the methodological quality and risk of bias in the included studies as per the Cochrane Collaboration for quality assessment. Quality assessment was performed by two independent reviewers (AP and FY), with any discrepancies adjudicated by a third reviewer (AH). The ROBINS-I tool assesses seven domains of bias: confounding variables, selection of participants, classification of interventions, deviations from intended interventions, incomplete outcome data, outcome assessment, and selective outcome reporting. This tool

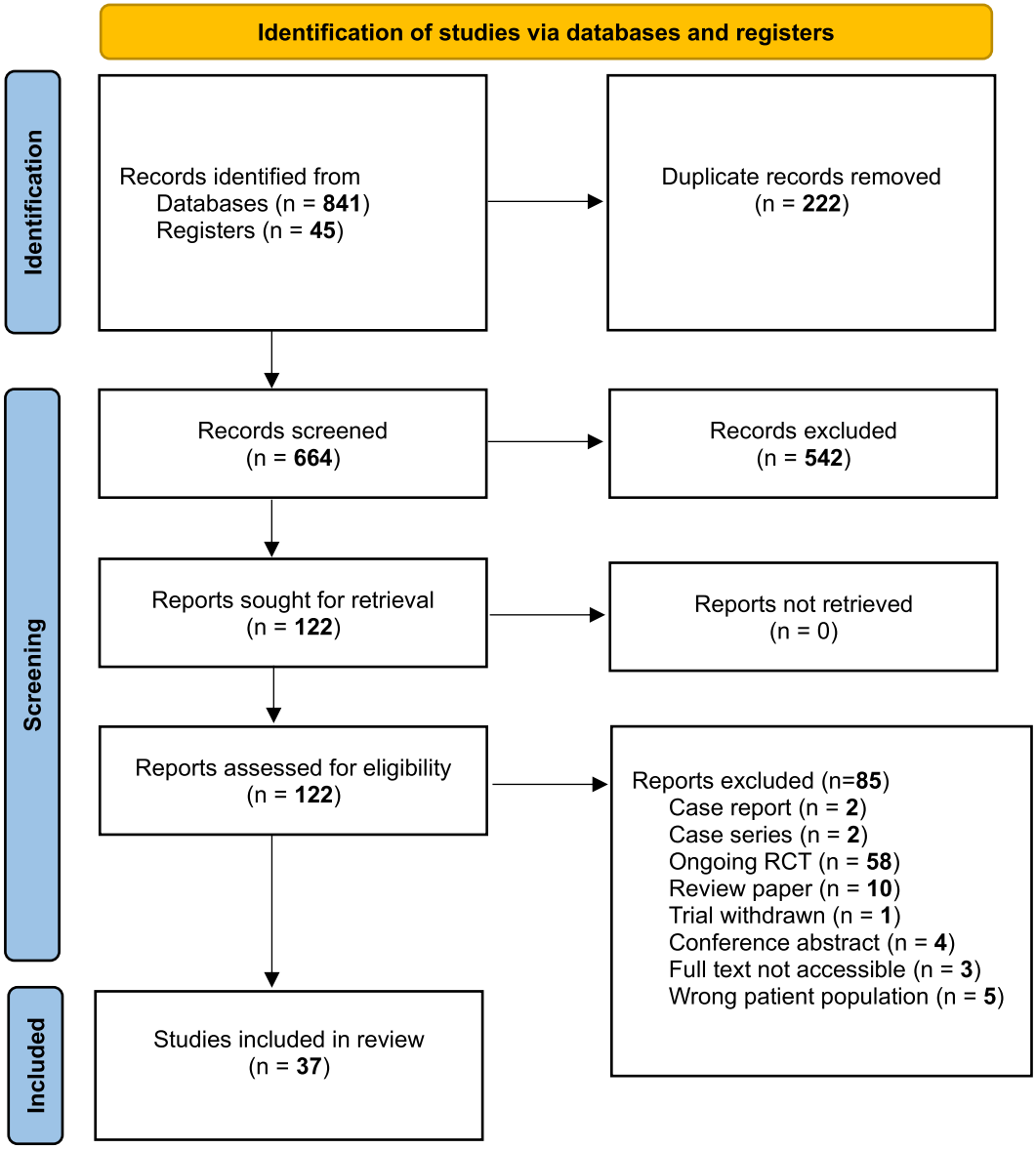

Fig. 1. PRISMA flow diagram of literature search and study selection process.

categorises studies as having an overall risk of bias that is 'low,' 'moderate,' 'serious,' 'critical,' or 'no information to base a judgement.' Conversely, ROB 2 assesses the risk of bias in RCTs based on five sources of bias: randomisation, deviations from established interventions, incomplete outcome data, outcome assessments, and selective outcome reporting. This tool provides a judgment about the overall risk of bias as 'low,' 'high,' or 'having some concerns'.

2.6. Statistical analysis

Meta-analysis was conducted using STATA v.18, applying a random-effects model when I^2 exceeded 50 %, indicating substantial heterogeneity. The effects of RLRL were analysed by intervention duration (6 and 12 months) and through a subgroup analysis based on the power or irradiance of RLRL devices: devices with low laser power of $\leq$ 0.6 mW (range, 0.29 to 0.6 mW) and devices with high laser power of $>$ 0.6 mW (range, 0.7 to 1.20 mW) [47,48]. Outcomes included mean changes in SER, AL, and subfoveal ChT from baseline to the end of the follow-up period. Clinical and methodological heterogeneity were assessed by comparing study characteristics, forest plots, and Egger's regression test. Statistical heterogeneity was evaluated using the Cochran Q test and I^2 statistic [43,49,50]. Results were expressed in millimetres (mm) for AL, dioptres (D) for SER, and microns (μm) for subfoveal ChT. For short-term light exposure studies, outcomes were presented as mean ± SD differences between light conditions.

3. Results

3.1. Literature search results

The database search strategy yielded 886 studies, with 664 remaining after the removal of duplicates (Fig. 1). After screening titles and abstracts, 122 studies were selected for full-text review. A total of 37 studies were included in the review: 19 RCTs, three non-randomised controlled trials, 13 observational cohort or case control studies, and two retrospective studies. Of the 19 RCTs, eleven RCTs met the pre-specified criteria for the meta-analysis (five with 12-month and four with 6-month outcomes). The remaining RCTs were excluded from the

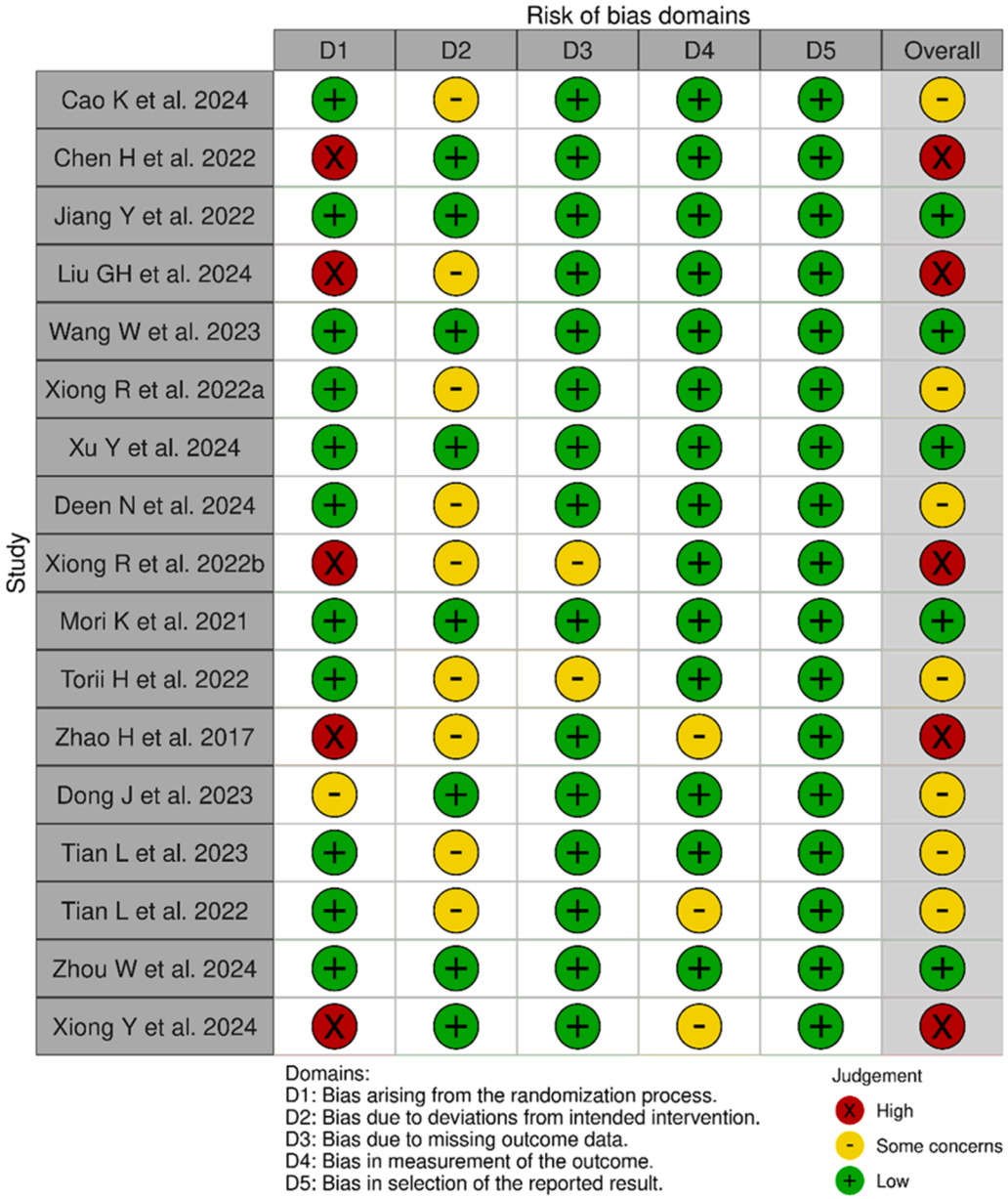

Fig. 2. Traffic light plot of Cochrane risk-of-bias tool for randomized trials (RoB2).

meta-analysis due to the following reasons: repeated analysis in the same study population ($n = 3$) [51–53]; assessed outcome variables at 3 and 24 months which fell outside the predefined inclusion criteria of 6 and 12 months ($n = 2$) [54,55] and one paper each investigated the effects of short-wavelength light at 6, 12 and 24 months [30,31,56]. Studies that assessed outcome variables at 3 and 24 months were included for systematic review and descriptive analysis [30,54,55,57,58].

3.2. Quality assessment

Risk of bias was assessed using the ROB 2 tool for RCTs and ROBINS-I for non-randomised studies (Figs. 2 and Supplementary Figure 1). All RCTs met the criteria for most domains, except five which showed potential randomisation bias due to inadequate methods or unclear reporting. Several studies reported concerns related to missing data, outcome measurement, and intervention classification. All non-randomised studies met most criteria, with the main issues identified in the domains pertaining to uncontrolled confounding and selection bias.

3.3. Assessment of publication bias

Egger's test was performed to assess the presence of publication bias in the studies included in the meta-analysis [59] and this showed no significant evidence of publication bias (intercept= 1.05, $p > 0.05$) for all the outcome measures (AL, SER or ChT) at 6 and 12 months. Funnel plots were generated to visually inspect for asymmetry, and Egger's test was used to statistically evaluate these (Supplementary Figures 2 and 3).

3.4. Study characteristics

3.4.1. Intervention characteristics

Supplementary Table 2 summarises the included studies: 24 focused on the long-term effects [30–32,48,51–58,60–71] and 11 investigated the short-term effects of monochromatic light exposure on ocular biometry and refraction [34–37,72–78]. Among long-term studies, 22 used long-wavelength RLRL therapy [48,51–55,57,58,60–71], while four examined short-wavelength blue (narrowband light centred on 454 nm, 455 nm or 456 nm) and violet light [30–32,56].

RLRL therapy was delivered using Class 1 laser emitting devices (power ranging from 0.16 to 2 mW and wavelengths of 635 or 650 nm) in twice daily three-minute sessions, five to seven days per week, with a minimum interval of four hours between sessions. Outcomes were compared with single vision spectacles or contact lenses.

In the short-term studies, three utilised RLRL (650 nm) [72,73,78], four employed monochromatic light emitting diode (LED)-based lighting (including 620 nm to 638 nm red, 875 nm near infra-red, 523 nm green, 454 nm to 456 nm blue, and 507 nm cyan) [34–37], and four focused on other forms of light stimulation such as 470 nm blue light stimulation of the optic nerve head, or digitally filtered long-(620 nm to 638 nm) and short-wavelength (450 nm) light [74–77]. LED based studies reported irradiance levels of 0.00435–3.25 W/m^2 [34–37] and varied exposure durations from ten minutes to two hours.

3.4.2. Participant characteristics

Long-term studies included children aged 3–18 years (mean ± SD 9.91 ± 1.46 years), while short-term studies mainly included young adults aged 18–35 years (mean ± SD 25.45 ± 2.92 years), with three involving children (see Supplementary Table 2). The RLRL studies were conducted primarily on participants of Chinese ethnicity, with one study including multi-ethnic groups [54].

3.5. Long-term effects of monochromatic lighting

Several trials and experimental studies (Supplementary Table 2) examined the long-term effects of long- and short-wavelengths of monochromatic light as an intervention to slow myopia progression, using RLRL devices or light-emitting glasses or filters.

3.5.1. Axial length changes

Long-wavelengths of light: The effectiveness of long-wavelength light on AL elongation was observed in studies involving RLRL therapy, synthesized from 11 RCTs evaluating outcomes at 6 and 12 months (Fig. 3A and 3B). The pooled results from the meta-analysis demonstrated a significant mean reduction in AL at 12 months between the RLRL and control groups, with a mean difference of –0.36 mm (95 % CI:0.41 mm to –0.31 mm, $I^2 = 67.73$ %, $p < 0.001$). A similar reduction was observed at 6 months, with a mean difference of –0.24 mm (95 % CI:0.28 mm to –0.20 mm, $I^2 = 41.25$ %, $p < 0.001$). However, at 6 months, the effects of RLRL therapy on AL varied significantly depending on the power of red light. The results from studies using higher powered laser devices showed a greater reduction in AL, with a mean difference of –0.27 mm (95 % CI:0.34 mm to –0.20 mm, $I^2 = 36.60$ %, $p < 0.001$), compared to studies using lower powered laser devices, which showed a mean difference of –0.22 mm (95 % CI:0.26 mm to –0.18 mm, $I^2 = 18.49$ %, $p < 0.001$). Additionally, the studies evaluating AL changes over 2, 3 and 24 months reported a mean difference of –0.11 mm (95 % CI:0.22 mm to –0.01 mm), –0.10 mm (95 % CI:0.15 mm to –0.06 mm) and –0.48 mm (95 % CI:0.72 mm to –0.24 mm) in AL between the RLRL and control groups, respectively.

Short-wavelengths of light: Four studies (three RCTs and one retrospective study) investigated the effects of short wavelengths (ranging from 360 to 500 nm) using either light-filtering glasses or contact lenses in children with myopia (Supplementary Table 2). The cumulative mean difference in AL between the treatment and control groups was not statistically significant. Specifically, the mean differences reported at 6, 12 and 24 months were –0.09 mm (95 % CI:0.17 to –0.02), –0.04 mm (95 % CI:0.15 to 0.07), and –0.03 mm (95 % CI:0.10 to 0.04), respectively.

3.5.2. Spherical equivalent refraction changes

Long-wavelengths of light: The changes in SER from 11 RCTs using RLRL therapy were meta-analysed at 12 and 6 months of treatment period. Fig. 4A and 4B illustrate that the cumulative effect of RLRL therapy on SER increased with the duration of the treatment. The pooled data showed significantly less myopia progression in the RLRL group compared to the control group, with a mean difference of 0.77 D (95 % CI: 0.64 D to 0.90 D, $I^2 = 65.35$ %, $p < 0.001$) at 12 months, and 0.31 D (95 % CI: 0.21 D to 0.41 D, $I^2 = 50.38$ %, $p < 0.001$) at 6 months of follow-up. Notably, at 6 months, the effects of RLRL therapy on SER varied significantly with the irradiance or power of the red light. The pooled results from studies using higher powered devices showed a significantly smaller myopic shift of 0.40 D (95 % CI: 0.27 to 0.52, $I^2 = 0$ %, $p < 0.001$), compared to studies using lower powered devices, which reported a change of 0.26 D (95 % CI: 0.12 to 0.40, $I^2 = 59.39$ %, $p < 0.001$). Similarly, studies reporting SER changes over 2, 3 and 24 months, showed less myopic shift in the RLRL group compared to the control group. The corresponding mean differences between the two groups were 0.32 D (95 % CI:0.17 to 0.81) over 2 months, 0.29 D (95 % CI: 0.09 to 0.50) over 3 months, and 0.93 D (95 % CI: 0.41 to 1.45) over 24 months.

Short-wavelengths of light: Four studies reported changes in SER with exposure to violet or blue light. However, no statistically significant difference was found in the total change in SER between the treatment and control groups at 6, 12 and 24 months (Supplementary Table 2). The corresponding mean differences were 0.48 D (95 % CI: 0.14 to 0.82) at 6 months, 0.04 D (95 % CI:0.16 to 0.24) at 12 months and 0.11 D (95 % CI:0.17 to 0.39) at 24 months.

3.5.3. Choroidal thickness changes

Seven RCTs reported the effects of RLRL therapy on subfoveal ChT

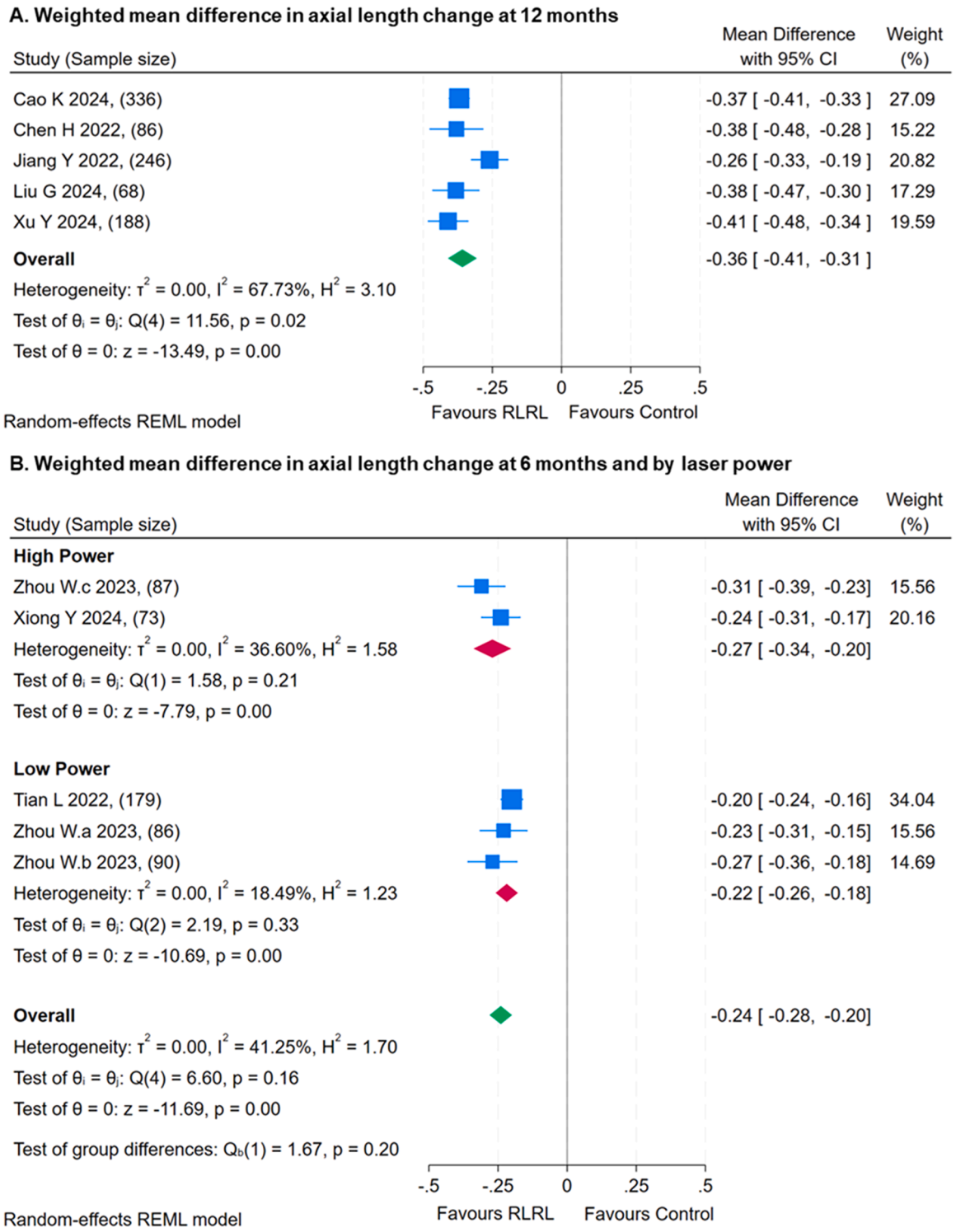

Fig. 3. Forest plot of mean difference in the axial length change between Repeated Low-Level Red-Light therapy and control group. (A) 12 months mean difference between Repeated Low-Level Red-Light therapy and control. (B) 6 months mean difference between Repeated Low-Level Red-Light therapy, and control categorised by laser power of the device. The a, b and c in referenced studies do not indicate separate studies they indicate a single study divided into three sub-groups of (a) 0.37 mW (b) 0.6 mW and (c) 1.2 mW.

(Fig. 5A and 5B). The pooled mean difference between the RLRL and control groups indicated a significant increase in the subfoveal ChT of +32.12 μm (95 % CI: 23.45 μm to 40.79 μm, $I^2 = 39.11$ %, $p < 0.001$) after 6 months and +31.78 μm (95 % CI: 21.24 μm to 42.32 μm, $I^2 = 76.58$ %, $p < 0.001$) after 12 months of treatment. However, at 6 months, the effects of RLRL therapy on subfoveal ChT varied significantly based on the irradiance of the red light. High powered RLRL devices (0.9 to 1.20 mW) resulted in a substantial thickening in subfoveal ChT, with a pooled mean difference of +38.93 μm (95 % CI: 25.45 μm to 52.40 μm, $I^2 = 0$ %, $p < 0.001$) between the RLRL and control groups. Lower powered RLRL devices (0.29–0.06 mW) led to a moderate increase in subfoveal ChT, with a pooled mean difference of +29.27 μm (95 % CI: 18.60 μm to 39.94 μm, $I^2 = 49.51$ %, $p < 0.001$) between the two groups. At 24 months (Supplementary Table 2), the RLRL therapy

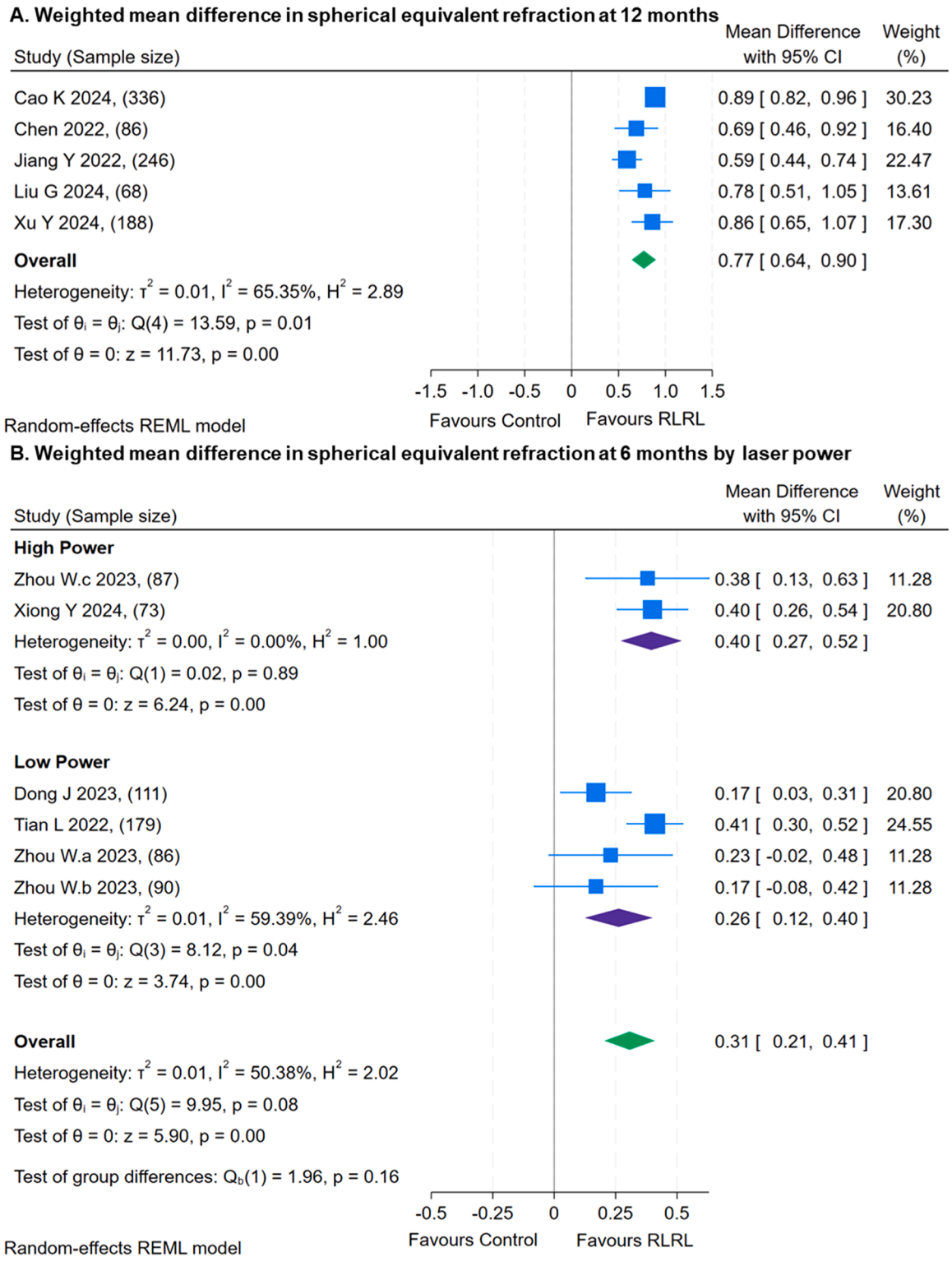

Fig. 4. Forest plot of mean difference in the spherical equivalence refraction between Repeated Low-Level Red-Light therapy and control group. (A) 12 months mean difference between Repeated Low-Level Red-Light therapy and control. (B) 6 months mean difference between Repeated Low-Level Red-Light therapy, and control categorised by laser power of the device. The a, b and c in referenced studies do not indicate separate studies they indicate a single study divided into three sub-groups of (a) 0.37 mW (b) 0.6 mW and (c) 1.2 mW.

group showed a significant increase in subfoveal ChT compared to the control, with a mean difference of +37.58 μm (95 % CI: 14.70–60.46 μm). Changes in subfoveal ChT were not reported with relation to short-wavelengths lights in any studies.

3.6. *Short-term effects of monochromatic lighting*

A small number of studies investigated the short-term effects of different monochromatic lighting with predefined irradiance levels on ocular biometry, specifically AL [34,36,37,78] and ChT [34–36,72,73]

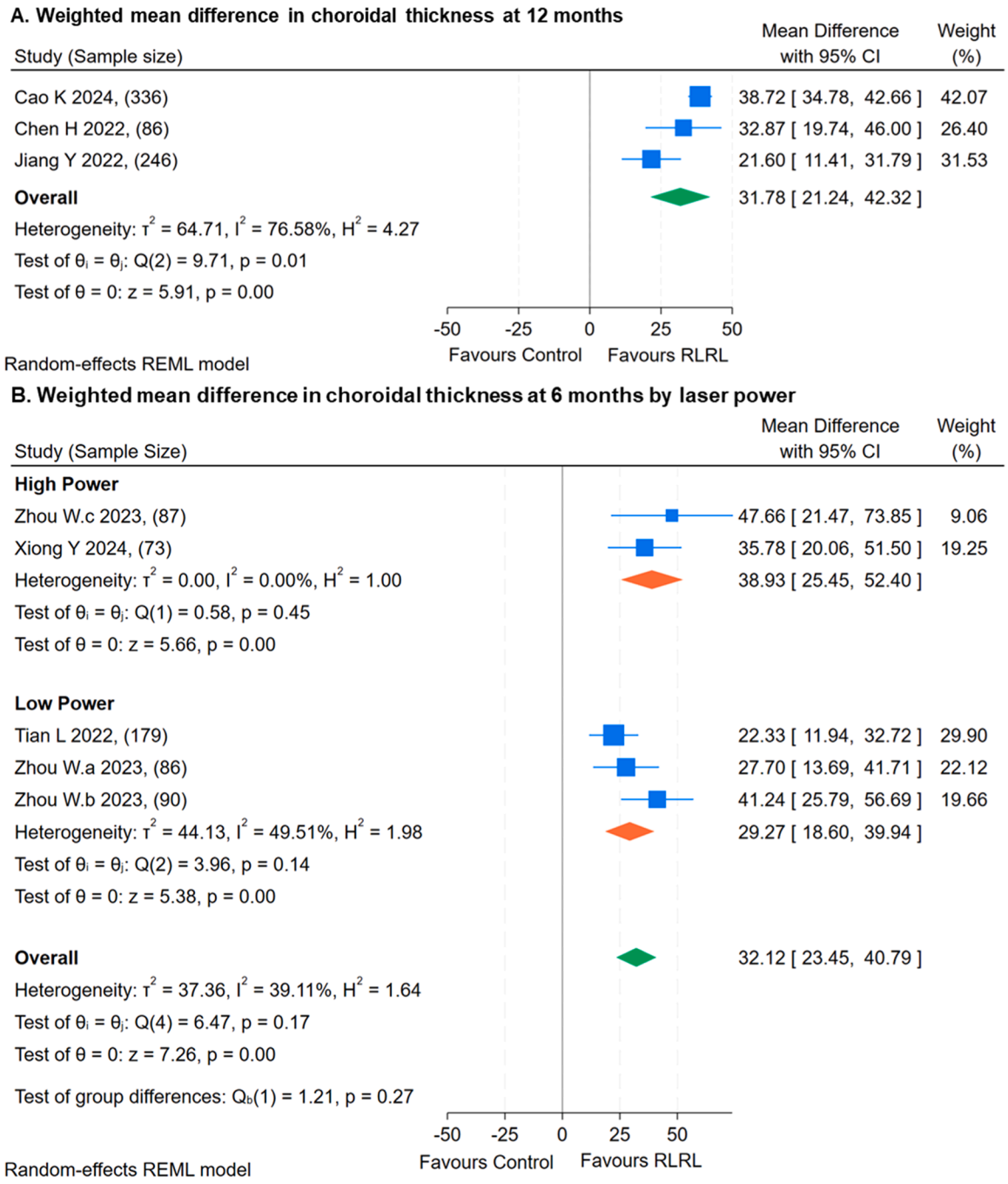

Fig. 5. Forest plot of mean difference in the choroidal thickness between Repeated Low-Level Red-Light therapy and control group. (A) 12 months mean difference between Repeated Low-Level Red-Light therapy and control. (B) 6 months mean difference between Repeated Low-Level Red-Light therapy, and control categorised by laser power of the device. The a, b and c in referenced studies do not indicate separate studies they indicate a single study divided into three sub-groups of (a) 0.37 mW (b) 0.6 mW and (c) 1.2 mW.

3.6.1. Red and blue light

3.6.1.1. Changes in axial length. Short-term exposure (10–120 min) to narrowband red (620–638 nm) and blue (454–456 nm) light induced opposite effects on AL in young adults. Recent studies by Thakur et al. and Chakraborty et al. found that exposure to red light significantly increased AL compared to blue light [34,36]. Thakur et al. observed that a one-hour exposure to red light led to a significant increase in AL, regardless of the presence or absence of hyperopic retinal defocus induced with minus lenses [34]. The mean differences between the blue and red light conditions was 0.019 ± 0.002 mm in the defocused eye and 0.012 ± 0.003 mm in the focused eye. Similarly, Chakraborty et al. reported a mean difference of 0.010 ± 0.002 mm in AL between blue and red light after two hours of exposure [36]. In contrast, Swiatczak et al. observed that ten-minutes of monocular exposure to red light using an integrated LED broadband light source and a narrow-band red filter placed over the eye resulted in a significant reduction in AL of 0.013 ± 0.017 mm in non-myopic individuals compared to participants with myopia [37] These changes in AL were reported to be transient, with participants recovering to baseline within 20–30 min of light offset [34, 36].

3.6.1.2. Changes in choroidal thickness. Previous studies have observed that exposure to red LED light induces greater choroidal thinning

compared to blue light in young adults. Lou et al. reported significantly more choroidal thinning under red light, with a mean difference of −5.12 ± 4.75 μm between the two lighting conditions [35]. Similarly, another study reported that red light caused choroidal thinning compared to blue light in hyperopic defocused eyes [34]. Chakraborty et al. also found thinning of choroid after two hours with a difference of −6.00 ± 2.00 μm between the red and blue light conditions [36]

Conversely, RLRL therapy (650 nm), applied twice daily (3 min per session) over four weeks, resulted in a relative mean increase in subfoveal ChT of +16.2 μm in children [72] and +18.38 μm in young adults [78]. However, another study found no significant changes in subfoveal ChT after a single 3-minute exposure to RLRL measured after 60 min [73]

3.6.2. Cyan light

A recent study found that a two-hour exposure to narrowband cyan light (507 nm) resulted in a significant reduction in AL, with a mean difference of 0.010 ± 0.003 mm in young adults and 0.016 ± 0.004 mm in children. Additionally, exposure to cyan light also led to a significant increase in ChT, with a mean increase of +8.0 ± 2.0 μm in young adults and +14.0 ± 2.0 μm in children [36].

3.6.3. Other forms of monochromatic light stimulation

Several recent studies have used various forms of light stimulation (other than diffuse retinal illumination) to examine changes in ocular biometry [74–77] Clement et al. found that exposure to both short-wavelength (450 nm) and long-wavelength (635 nm) light for 30 min increased AL, with significant choroidal thinning occurring only with long-wavelength light after stimulating a 12° retinal area in dominant eyes [76] Hoseini et al. observed increased subfoveal ChT (7.00 ± 1.00 μm) and decreased AL (0.006 ± 0.003 mm) 60 min after a 1-minute exposure of 12 Hz flickering blue (460 nm) light to the optic nerve head, while red (620 nm) light had the opposite effect [75]. Chakraborty et al. investigated the effects of melanopsin stimulation on AL changes with 5-second exposures to red (625 nm) and blue (470 nm) light following two hours of induced myopic (+3.00 D) or hyperopic (−3.00 D) retinal defocus in emmetropic individuals [74]. They found that melanopsin stimulation with blue light exaggerated the change in AL following hyperopic defocus, resulting in a mean AL increase of ~ +0.018 mm, greater than that caused by hyperopic defocus alone. No effect on AL was observed with myopic defocus under either red or blue light. Finally, Barbara et al. investigated the effect of digitally low pass filtering either the red channel ('blue in focus') or blue channel ('red in focus') according to the human LCA function, and evaluated the effect on AL [77]. They reported a significant increase in AL with blue-in-focus movies (450 nm), while red-in-focus movies (630 nm) led to a reduction in AL after 45 min of viewing. These AL changes were observed in emmetropic, but not myopic eyes.

4. Discussion

This systematic review provides a holistic and contemporary overview of the use of chromatic light interventions in myopia control, while also shedding light on potential directions for future light-based interventions. The pooled results from long-term RCTs revealed that long wavelengths (635–650 nm), used in RLRL therapy, were the most effective in controlling axial growth and myopia progression, while the effects of violet light (360–500 nm) were inconsistent and weaker when measured over 6 to 12 months. Short-term exposure to both long and short wavelengths for 60–120 min also induced significant changes in ocular biometry, but in the opposite direction.

4.1. Repeated low-level red light therapy and myopia

Animal studies in rhesus monkeys and tree shrews show that exposure to long-wavelength light slows ocular growth and reduces myopia by inducing choroidal thickening [79,80]. In humans, the use of long-wavelength light in the form of RLRL has consistently been effective in slowing axial elongation and SER progression compared to SVS, or single vision contact lenses. Our findings of AL and SER changes at 6 and 12 months with RLRL are consistent with another recent meta-analysis [29].

Our subgroup analysis showed a dose-response relationship in the efficacy of RLRL treatment in myopia control, depending on the power of the RLRL device. We found that RLRL devices with higher power (> 0.6 mW) significantly enhanced the effectiveness of the therapy compared to low power (≤ 0.6 mW) devices. Despite extensive evidence supporting the potential of RLRL, studies have reported a strong rebound effect after discontinuation [81], highlighting the need for more long-term studies.

Proposed mechanisms underlying RLRL's anti-myopiagenic effects include the restoration of scleral collagen levels by increasing fibroblast growth, enhancement of mitochondrial cytochrome C function, and improved ocular blood circulation [82–84]. While most studies claim RLRL to be safe, the long-term effects on ocular structures and function remain unknown [85]. A recent study found decreased cone density in the paracentral fovea after one year of RLRL therapy in children [86], while another case report described structural and functional foveal damage after five months of RLRL in a 12-year-old female [87]. Ostrin and Schill cautioned the potential risk of thermal and photochemical damage from the light (0.16 - 2 mW) used in two RLRL devices [47]. They demonstrated that continuous exposure for 180 s exceeds the maximum permissible exposure for these devices, as the ANSI Z136.1–2014 standard (https://www.lia.org/) recommends a limit of 100 s for Class 1 lasers with a maximum power of 0.4 mW. Based on our review, it is possible that children treated with high irradiance RLRL devices may be at a higher risk of photochemical retinal damage [48,67] Very recently, the China National Medical Products Administration (NMPA) reclassified RLRL devices as Class III lasers, prompting significant regulatory changes for their existing manufacturing and sale.

In this review, only a limited number of studies have examined the changes in ChT in response to RLRL treatment [48,60–62,66,67] Though choroidal thickening (+32.12 μm after 6 months, +31.78 μm after 12 months of RLRL) was a consistent outcome with other myopia control interventions [88–90], it accounts for only ~28 % of AL reduction [51], indicating involvement of other potential mechanisms.

4.2. Violet light transmitting glasses and myopia

Our review found that violet light-transmitting single-vision glasses [30,32] and violet light-emitting frames [31] were relatively less effective in controlling AL and myopia progression in children. In contrast to RLRL, few studies have demonstrated the efficacy of violet light in controlling myopia progression. This effect could be mediated by retinal opsin 5 (OPN5) signalling [91]. AL reductions reported with violet light devices were modest (0.03 to 0.09 mm over 6 – 24 months), which was likely due to the absorption of UV light through the crystalline lens reducing the amount of light reaching the retina [92]. Another recent RCT also found no significant effect of blue-violet light-filtering glasses in controlling axial elongation over 12 months, with a mean difference of 0.04 ± 0.29 mm between the test and control groups [56]. No studies have investigated rebound or adverse effects after treatment cessation, though one recent case of retinal injury was reported after 20 s of exposure to a 410 nm violet LED in a 15-year-old male [93]. Additionally, violet-light-transmitting eyeglasses require a minimum amount of outdoor time to be effective, [30], which could pose an implementation challenge for children with limited outdoor exposure. More research is needed to assess the safety and efficacy of violet light exposure to eye.

The difference in the effects of RLRL and violet light therapy may be attributed to the mode of light delivery. RLRL typically involves the child viewing into a device that provides targeted stimulation, whereas

violet light is generally administered through light-emitting glasses (resulting in more diffuse exposure) or passive optical filtration. Whether violet light therapy delivered via a device designed to target the macular region could yield a greater impact on myopia progression remains unknown and warrants further investigation.

4.3. Short-term ocular changes to narrowband wavelengths

Short-term exposure to blue light (up to 60 min) has been shown to induce small but significant choroidal thickening and AL reduction in human subjects [34–36]. These effects are thought to be mediated by the activation of short-wavelength-sensitive cones [94] and melanopsin-containing retinal ganglion cells [95]. However, the precise underlying mechanisms remain unclear, and the long-term effects of short-wavelength light exposure have yet to be fully elucidated.

Notably, AL elongation and choroidal thinning observed with short-term exposure to red LED light contradict recent studies and clinical trials involving RLRL, which have shown significant choroidal thickening and protection against myopia progression and axial elongation in children. These differences may stem from the type of light used (semiconductor laser diodes in RLRL vs. LEDs in short term studies), as well as frequency and duration of exposure. The observed differences may be attributed to RLRL's targeted stimulation of the macular region, in contrast to the more diffuse stimulation provided by LED. Since laser devices generate coherent light, laser speckles can more effectively stimulate mitochondria activity, promoting forward scattering [96] and deeper penetration compared to non-coherent LED light [97].

Interestingly, we observed inconsistencies in the effect of red light on AL across short-term studies. For instance, a 10-minute exposure to integrated LED broadband light filtered through a narrowband red filter placed over one eye resulted in axial shortening, but only in non-myopic eyes, with no significant change observed in myopic eyes [37]. This differential response may be attributed to the reduced sensitivity of myopic eyes to LCA [77]. More importantly, the AL shortening reported by Swiatczak et al. contrasts with findings from other short-term studies, which demonstrated AL elongation following 60–120 min of red-light exposure [35,36]. These discrepancies may be attributed to methodological differences, such as direct retinal exposure to red light versus filtered light delivery, or from variations in exposure duration across studies.

Age-related physiological differences may influence ocular responses to light-based interventions. Most long-term studies have been conducted in children aged 3 to 18 years, while short-term effects have primarily been examined in young adults (except for one study by Chakraborty et al [36]). However, the effects of chromatic light exposure on ocular biometry appear to be consistent across age groups. For example, Chakraborty et al. reported similar changes in AL and ChT in both children (8–15 years) and young adults (18–28 years) following short-term exposure to narrowband wavelengths. Similarly, RLRL therapy has demonstrated comparable effects, such as AL shortening and choroidal thickening, in young myopic adults (18–35 years), consistent with findings previously observed in paediatric populations [78].

4.4. Newer light-based interventions and myopia

Recently, studies have investigated the potential efficacy of chromatically simulated myopic defocus for modulating ocular biometry in humans. Swiatczak et al. showed exposure to digitally simulated myopic defocus by low pass filtering the blue channel (keeping "red in focus") on a computer screen for 45 min significantly thickened the choroid and reduced AL in emmetropic eyes, but not myopic eyes [77]. Interestingly, exposure to the same digitally simulated myopic defocus for 2 h per day over 12 consecutive days caused progressive thickening of choroid and shortening of AL in myopic subjects, indicating that the myopic retina probably needs longer repeated chromatic stimulations for myopia control [98]. Another innovation is blind spot stimulation using blue light (MyopiaX®, Dopavision GmbH) through a digital application (https://dopavision.com/science/). The app operates on a standard mobile phone, which is placed into a virtual reality headset to stimulate the blind spot in both eyes. Blue light (around 480 nm) is known to stimulate melanopsin photopigment, which can modulate the release of dopamine in the inner retina through activation of dopaminergic amacrine cells [99]. Early data from a MyopiaX-1 trial demonstrated moderate efficacy in controlling axial growth and myopia progression compared to myopia control spectacles, while also supporting the safety and tolerability of the intervention in children aged 6–14 years [100].

4.5. Strength and limitations

A key strength of this review is the meta-analysis of RLRL studies with consistent methodology, uniform follow-up durations, and inclusion of RCTs with no significant publication bias. This review integrates evidence from both long-term RCTs and short-term experimental studies to provide a comprehensive and up-to-date overview of the effects of wavelength and chromaticity on ocular biometry and myopia progression. However, some RCTs showed randomisation bias, and most non-RCTs had risks related to confounding and selection bias. Additionally, due to the limited number of studies in the meta-analysis, a sensitivity analysis could not be conducted to address heterogeneity. Given that all clinical trials investigating RLRL therapy were conducted in China, and those assessing violet light interventions in Japan, the reported effect sizes may have limited generalisability. Participants from diverse ethnic backgrounds may exhibit different responses to chromatic interventions, underscoring the need for broader, more inclusive studies.

5. Conclusion

In conclusion, this review has highlighted how exposure to different wavelengths and various light-based interventions, both in the long- and short-term, can influence ocular biometry and modulate myopia progression in humans. While the promising outcomes of RLRL therapy as a myopia management intervention are noteworthy, the efficacy of violet light has thus far demonstrated only modest effects. Key questions remain regarding the clinical translation of these findings: how can light-based interventions be effectively and safely implemented into routine clinical practice? While active light stimulation, such as RLRL therapy, violet light exposure and MyopiaX, appears effective, do issues of patient adherence and long-term safety limit their clinical utility? Could passive light modulation through optical filters offer a more practical and sustainable solution for myopia control? How can short-term experimental studies contribute to the development and optimisation of light-based chromatic interventions? Addressing these questions will be critical for the successful translation of emerging light-based strategies into clinical myopia management.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jpap.2025.100268.

Data availability

Data will be made available on request.

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