INTRAOPERATIVE EVALUATION OF THE INTESTINAL WALL VIABILITY

N.A. Adamenkov[1, 2], A.V. Mamoshin[1, 3], V.V. Dremin[1], E.V. Potapova[1], V.V. Shupletsov[1], Yu.V. Ivanov[4], D.N. Panchenkov[5], A.V. Dunaev[1]

[1] Orel State University, Orel, Russia;

[2] Orel Regional Clinical Hospital, Orel, Russia;

[3] National Medical Research Center of Surgery named after A. Vishnevsky, Moscow, Russia;

[4] Federal Research and Clinical Center of Specialized Medical Care and Medical Technologies, Moscow, Russia;

[5] Russian University of Medicine, Moscow, Russia

ABSTRACT

An analysis of data from national and foreign literature was carried out in terms of intraoperative determination of the intestinal viability in cases of developing the diseases in the abdominal cavity organs, associated with impaired intestinal blood supply. The basis of this work is the analysis of the modern literature on the methods of intraoperative evaluation of mesenteric ischemia. Impaired mesenteric blood supply is often the consequence of a number of reasons of developing critical conditions (mesenteric thrombosis, acute adhesive intestinal obstruction, incarcerated hernia etc.), also representing a high risk factor for lethal outcomes. Special attention is paid to the occlusion-related pathogenetic mechanism of developing mesenteric ischemia, which is accompanied by rapid development of irreversible morphological changes in the tissues and by significant disorders in the homeostasis systems of the organism. The generally available method for visual evaluation of the intestine viability is not always valid in terms of determining the degree of intensity of the ischemic changes in the intestinal wall. The algorithm of determining the intestine viability includes the determination of the intestine color, the peristaltic motions, the pulsation and the blood filling of mesenteric vessels with dynamic evaluation of these signs after the injecting the local anesthetic drug solution into the mesenterium and after "warming" the intestine with towels soaked in warm sodium chloride solution. In the current surgical conditions, a more precise method is required for intraoperative determination of the tissue viability. For the purpose of the objective evaluation of the intestinal blood supply, the recommendations include using intraoperative ultrasonic and laser Doppler flowmetry, as well as the regional transillumination angiotensometry of the intramural vessels in the small intestine. At the same time, a number of optical spectroscopy and visualization methods show high sensitivity to changes in blood microcirculation without using exogenous contrasting, which can also be successfully used when evaluating the intestinal circulation. According to data from modern literature, there is still controversy on the efficiency of various methods for intraoperative evaluation of disorders of the regional blood microcirculation and the intestine viability, which justifies the conduct of further research works.

Keywords: *intestine; ischemia; viability; biomedical optics; perfusion.*

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INTRODUTION

According to clinical recommendations from the World Society of Emergency Surgery (WSES), acute mesenteric ischemia develops in case of sudden cessation of intestinal blood supply, leading to cell damage, necrosis of the intestinal wall and death of the patient. Intestinal ischemia can have an occlusion-related or a non-occlusive origin. The occlusion-related pathogenetical mechanism includes the embolism of the mesenteric artery (50%) and the thrombosis of the mesenteric artery (15–25%) or vein (5–15%) [1]. The prevalence of non-occlusive ischemia, according to data from J. Canceco et al. [2] from the California University, is 25%. Non-occlusive ischemic lesions

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ИНТРАОПЕРАЦИОННАЯ ОЦЕНКА ЖИЗНЕСПОСОБНОСТИ КИШЕЧНОЙ СТЕНКИ

Н.А. Адаменков[1, 2], А.В. Мамошин[1, 3], В.В. Дрёмин[1], Е.В. Потапова[1], В.В. Шуплецов[1], Ю.В. Иванов[4], Д.Н. Панченков[5], А.В. Дунаев[1]

[1] Орловский государственный университет имени И.С. Тургенева, Орёл, Россия;

[2] Орловская областная клиническая больница, Орёл, Россия;

[3] Национальный медицинский исследовательский центр хирургии им. А.В. Вишневского, Москва, Россия;

[4] Федеральный научно-клинический центр специализированных видов медицинской помощи и медицинских технологий, Москва, Россия;

[5] Российский университет медицины, Москва, Россия

АННОТАЦИЯ

Проведён анализ данных отечественной и зарубежной литературы по вопросам интраоперационного определения жизнеспособности кишечника при заболеваниях органов брюшной полости, сопровождающихся нарушением кровоснабжения кишечника. Нарушение мезентериального кровоснабжения часто является следствием ряда причин критических состояний (мезентериального тромбоза, острой спаечной кишечной непроходимости, ущемлённой грыжи и др.) и фактором высокого риска летального исхода. Особое внимание уделяется окклюзионному патогенетическому механизму возникновения мезентериальной ишемии, которая сопровождается быстрым развитием необратимых морфологических изменений тканей и выраженным нарушением системы гомеостаза организма. Общедоступный метод визуальной оценки жизнеспособности кишки не всегда достоверен в определении степени выраженности ишемических изменений кишечной стенки. В алгоритм определения жизнеспособности кишки входит определение цвета кишечника, перистальтики, пульсации и кровенаполнения брыжеечных сосудов с динамической оценкой этих признаков после введения в брыжейку кишки раствора местного анестетика и «согревания» кишки салфетками, смоченными тёплым раствором хлорида натрия. В современных условиях во время хирургической операции необходим более точный интраоперационный способ определения жизнеспособности тканей. Для объективной оценки кровоснабжения кишечника рекомендуется использовать интраоперационную ультразвуковую, лазерную допплеровскую флоуметрию, регионарную трансиллюминационную ангиотензометрию внутристеночных сосудов тонкой кишки. Ряд оптических методов спектроскопии и визуализации имеет высокую чувствительность к изменению микроциркуляции крови без использования экзогенного контрастирования, что также может быть успешно использовано в оценке кровотока кишечника. Отсутствие однозначных рекомендаций в отношении эффективности различных методов интраоперационной оценки нарушений регионарной гемомикроциркуляции и жизнеспособности кишки обусловливает необходимость проведения дальнейших исследований.

Ключевые слова: *кишечник; ишемия; жизнеспособность; гиперспектральная камера; перфузия.*

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can develop in the patients with severe concomitant abnormal conditions, hypovolemia, as well as in the patients using vasoconstricting medicines [3, 4].

The surgical abdominal disorders causing intestinal ischemia also include such nosologies as incarcerated hernia, acute intestinal obstruction and mesenteric thrombosis.

According to clinical recommendations, the “Incarcerated hernia” [5] term is defined as the presence of an acute or gradual compression of one

or several abdominal cavity organs within the hernial orifice, which is accompanied by an impairment of the organ's blood supply and results in its necrosis. The hernial defects occur in 5% of population with a risk of incarceration being 1–3% of all the cases [6]. The prevalence of incarcerated hernia in the Russian Federation, according to data from A.Sh. Revishvili et al. [7], has been persisting for the last 3 years at a high level and equals to 36–37 cases per 100 000 of the adult population. In 2022, the number of patients hospitalized with incarcerated hernia was 19.3% higher comparing to the numbers reported during the last 20 years. V.I. Struchkov et al. [8] in their research work report that the hernial sac in 50% of the cases contains small intestine and in 21% — large intestine. Necrosis of the intestinal wall was observed in 9% of the cases [9].

By the degree of intestinal coverage, the incarceration can be complete and incomplete. The incomplete type of lumen coverage in the incarcerated organ includes the parietal Richter's hernia and the Littre's hernia [5]. The Richter's hernia is the incarceration of the antimesenteric part of the intestinal wall. As evaluated by the C.M. Regelsberger-Alvarez et al. [10], up to 10% of all the hernias are Richter's type ones. The frequency of developing necrosis with this hernia type reaches up to 69% at the moment of surgery. The Littre's hernia is a herniation of the Meckel's diverticulum and it is an extremely rare complication with a prevalence of up to 0.09% [11].

The main form of intestine incarceration within the hernial orifice, causing ischemia, is the antegrade one, which most frequently develops in case when a small opening exists in the muscle tissue along with a significant quantity of content within the hernia itself [6]. The retrograde form of incarceration, known as the Maydl's hernia, is represented by two intestinal loops in the hernial sac along with the third loop connecting them inside of the abdominal cavity [12]. Besides, another possible variant is the sudden incarceration at the hernial orifice in the absence of past medical history of hernia [5]. In case of the incarcerated hernia, the strangulation causes the venous stasis, which results in swelling of the intestinal wall, its impaired permeability and with blood/plasma elements entering the intestinal wall and the hernial sac. With this background, in the limited space of the hernial sac, the processes of intestinal content decomposition take place with the formation of toxins [13].

Acute intestinal obstruction is a syndrome integrating various non-oncological diseases, resulting in the impaired intestinal passage due to mechanical obstruction or insufficiency of the intestine's motor functions. By the mechanism of developing the acute intestinal obstruction, ischemia can be caused primarily by the strangulation form that includes the peritoneal adhesions of the abdominal cavity, the intestinal volvulus, the invagination and the closed-loop obstruction [14].

Adhesions of the abdominal cavity is a symptomless (developing without the impairment of the functions in the abdominal cavity organs) adhesion of the parietal and visceral peritoneum developing as a result of altered normal mesothelization stages [15]. The prevalence of peritoneal adhesions in the abdominal cavity reaches up to 93% in patients undergoing repeated abdominal cavity surgeries [16]. In the research work by R.P. Ten Broek [17], the rates of developing acute adhesive intestinal obstruction were reaching 2% of the total number of surgical patients admitted to the in-patient units. Adhesive obstruction of the small intestine represented 55–75% of the small intestine obstruction cases [18]. According to data from A.Sh. Revishvili et al. [7], the number of acute adhesive intestinal obstruction cases has increased by 8.6% comparing to 2021, while the hospital and postoperative mortality has decreased to the level of 2019 equaling 4.33% and 4.03%, respectively. There is no unambiguous opinion on the causes of developing adhesion process in the abdominal cavity [19], but most frequently it develops with a background of peritoneal impairment during surgical procedures [20]. The loss of tissue integrity during surgical intervention causes the activation of angiogenesis in the basal layer of the peritoneum, which causes the disruption of the fibrinolytic processes and initiates the formation of adhesions [21]. Upon damaging the peritoneum, the delaminated mesothelial cells express cellular adhesion molecules and various chemotaxis factors, which results in greater inflow of inflammatory cells, predominantly macrophages, producing inflammatory cytokines, such as interleukins 1 and 6 (interleukin, IL-1, IL-6) and the tumor necrosis factor (TNF). In the adhesion process, the main role belongs to IL-6, the potent inductors of which are IL-1 and TNF. These inflammatory reactions are directly proportional to the degree of peritoneal damage [22].

K.R. Pashkin et al. [23] report that the mesenteric volvulus represents 4–5% of all the types of intestinal obstruction. As for the location, the most common one is the sigmoid volvulus (60–75%), less frequent is the cecal one (20–35%), the jejunal (7–18%) and transverse colon volvulus (3–5%). Generally, the pathological process

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involves a large area of the intestine with significant necrobiotic changes and severe hemodynamical and systemic alteration of hemostasis [14]. According to the research by T.A. Nikanorova et al. [24], intestinal volvulus can be found in 5% of the whole cases in adults. In the pathogenesis of this type of intestinal obstruction, the main role is played by the strangulation and the obturation components. The obturation mechanism is caused by rigidity-related narrowing of the intestinal lumen resulted from the introduction of one part of intestine into the other part's lumen, while the strangulation mechanism is caused by the compression of mesenteric vessels of the intestine between the middle and internal segments of the invaginated part [25].

Among the severe forms of strangulation-related intestinal obstruction, 3–4% is represented by closed-loop obstruction, in which compression of the mesenteric vessels of both intestinal loops occurs, with one of which always being the jejunum [9].

In case of strangulation-related intestinal obstruction, the primary impaired component is the blood supply of the intestine involved into the process, which is caused by the compression of mesenteric vessels supplying the intestine and, as a result, it causes rapid necrosis of the intestinal wall. The second most often variant of developing intestinal obstruction is the obturation related intestinal obstruction. The main etiological factors of this type of intestinal obstruction include tumors of the large intestine, developing in 15–20% of the patients and occurring in all the age groups [26]. According to data for 2022 [7], the number of acute intestinal obstruction cases of tumor-related origin in the Russian Federation has decreased by 2.3% comparing to 2021, however, the hospital and postoperative mortality has increased, equaling 17.75% and 19.57% respectively. According to the materials from A.G. Khasanov et al. [27], the prevalence of gallstone-related obturation-type intestinal obstruction relative to the total number of observed intestinal obstruction ranges from 0.17% to 6.2%.

During the second phase of the acute intestinal obstruction (intoxication), an impairment of the intramural intestinal blood circulation takes place [28]. The blood supply of the area located above the obstacle is being impaired secondarily in connection with the over-extension with the intestinal contents due to massive fluid inflow into the intestinal wall and into the intestinal lumen, which results in systemic hypovolemia and hemoconcentration. The developing intestinal edema and decreased blood inflow/outflow lead to intestinal ischemia [29]. The ischemic impairment of the intestine is accompanied by a decrease in the adenosinetriphosphate production by cell mitochondria, by the activation of hydrolase, by the decreased selective permeability of cellular membranes and by the increase of calcium inflow into the ischemic cells. When the intestinal ischemia becomes critical, polyorgan insufficiency develops, being the main cause of mortality [30].

The traditional method for intraoperative determination of intestine viability is the Kerte's visual method [31] based on the color, the presence of peristaltic waves, pulsation, blood filling of vessels in the intestine, as well as the dynamic changes of these signs after injecting the local anesthetic agent into the mesenterium and after "warming" the intestine up using towels soaked in warm sodium chloride water solution (NaCl) with the weight percentage of NaCl being ~0.9% [14]. According to data from A. Karliczek et al. [32], the sensitivity of visual evaluation of the intestine viability is 61.3% with the specificity being 88.5%.

In 2020, a group of authors headed by A.A. Zakharenko [33] has published a review of such methods for objective intraoperative assessment of the intestinal viability as the ultrasonic Doppler sonography, the polarographic method, the laser Doppler flowmetry, the laser speckle-contrast visualization, the fluorescent angiography, the side-light dark-field microscopy, the optical coherent tomography and the micro-peritoneal dialysis. Laser fluorescent spectroscopy of oxidative metabolism co-enzymes was marked by this review as the potentially perspective intraoperative method for objective determination of the viability of the intestinal wall.

In 2022, a group of authors from Saint-Petersburg, headed by D.A. Vedyanskaya [34], has published a scientific review devoted to the modern methods of intraoperative evaluation of the perfusion of tissues, with the review focused on assessing the cutting edge methods for defining the microcirculation in the intestinal wall, in particular, the hyperspectral and ICG-visualization, as well as the photoplethysmography, taking into consideration the potential for its practical use and the necessity of large clinical trials.

In a literature review by A.A. Valiev et al. [35], devoted to the modern methods of assessing the viability of the intestine, it was reported that the most widespread method for intraoperative evaluation of the microcirculation in the intestinal wall is the visual one. In the opinion of the authors, fluorescent angiography, which is the widely used and most studied method,

along with the hyperspectral visualization and the multi-modal coherent tomography are the most promising methods of intraoperative assessment of the viability of the intestine.

In the research work from our group of authors, we have summarized the data from the current foreign and national literature on the methods of intraoperative objective assessment of the intestinal wall viability in case of acute surgical disorders associated with intestinal ischemia, on the types and the efficiency of the methods used, along with the demonstration of the results obtained when personally using the technologies of assessing the perfusion of the intestinal wall during an animal model experiment with using hyperspectral visualization.

METHODS OF INTRAOPERATIVE OBJECTIVE ASSESSMENT OF THE MICROCIRCULATION IN THE INTESTINAL WALL DURING THE COURSE OF SURGICAL PROCEDURES

Ultrasonic Doppler sonography

Ultrasonic Doppler sonography is a variation of ultrasound examination using the Doppler effect for the purpose of defining the level of circulation within blood vessels [36]. Intraoperative evaluation of the blood flow ultrasonography parameters in the mesenteric vessels is a credible criterion of intestinal viability [33]. In the research work by M. Cooperman et al. [37], involving more than 200 patients with colon resection, the usage of intraoperative ultrasonic Doppler sonography resulted in a decrease in the rates of anastomosis failure during the postoperative period down to 1%. However, the method, according to literature data, has a high number of false-positive and false-negative results [38], being practically comparable to visual evaluation [39]. The sensitivity of the method diminishes its contribution to the informative signal from the examined area due to the interference from the surrounding vascular structures [33].

Polarographic method

The polarographic method is based on registering the levels of interstitial fluid oxygen during the electrolysis process upon interacting with the charged electrode [40]. Based on the results of the research work by W.G. Sheridan et al. [41], direct intraoperative tissue oxymetry of the human gastrointestinal tract is applicable as the mean of evaluating the degree of oxygen saturation in the tissues. However, for the purpose of defining the viability of the intestinal wall, direct contact is required between the electrode and the serous layer of the intestine, while the precision of evaluating the perfusion of the intestinal wall does not exceed 57.7%.

Micro-peritoneal dialysis

Micro-peritoneal dialysis represents a method of obtaining biological fluids from the tissue during the metabolic process within the organism with its further compositional analysis [42–50]. The method is based on the diffusion of the analyte into the perfused fluid via the micro-peritoneal dialysis catheter, which is introduced into the tested tissue or near it [49, 50]. The differences in the perfusion of the intestinal wall are determined based on the levels of lactate, pyruvate, glucose and cytokines in the peritoneal dialyzate [44–46]. The invasiveness and the cost of the analyzers along with its expendables are the main downsides of this method [47].

Laser Doppler flowmetry

Laser Doppler flowmetry provides contactless optical measurements of blood perfusion in the microcirculation [48–51]. The method is based on the effect of Doppler shift used for the purpose of measuring the velocity of red blood cells by means of laser radiation [52]. This method is easily reproducible and it has sufficiently high sensitivity, also allowing for evaluating the perfusion degree and the microcirculation status in the examined tissue area. The specific feature of the method is the ability to assess the microcirculation in the examined area. This image is the result of overlaying the multidirectional movements of particles in great numbers of microvessels and the changes in the concentration of these particles in the given area [53]. A.I. Khripun et al. [54] have demonstrated the capabilities of intraoperative application of laser Doppler flowmetry as a fast, easily interpretable and effective method for assessing the perfusion of the intestine in cases of acute mesenteric arterial blood flow impairment, which was studied in a group of 109 patients. The method has shown high (91%) sensitivity when determining the viability margins for the small and large intestines. A significant decrease was demonstrated in the cases of intestinal necrosis in the early post-surgery period (from 48.6 to 9.1%) along with the decrease in the rates of postoperative complications (from 67.6 to 40.9%) [54]. The laser Doppler flowmetry method, being non-invasive and showing high measurement speed, does not reflect the whole variety of the capillary network of the

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intestinal wall, providing the possibility of registering the measured parameters in relative units only at a small examined area.

Laser speckle-contrast visualization

Laser speckle-contrast visualization is based on registering the accidental speckle-interference patterns, back-scattered from the surface of the tissue illuminated with the coherent laser with a wave length of λ=635 nm. The obtained image contains darker and lighter colored areas, based on the accidental speckle-interference figure, formed by changes in the back-scattered light. The shift of the intensity of particles moving inside the lighted area changes the fluctuation of the scattering radiation, registered by the detector, leading to changes in the patterns and in the spatial contrast of the speckles. The trial by S. Kojima et al. [55] has demonstrated the ability of laser speckle-contrasted visualization to adequately measure the changes in the perfusion of the intestine with outstanding reproducibility. Similar results were reported by R. Ambrus et al. [56], showing that the changes in the laser speckle-contrasted visualization show good correlation when assessing the microcirculation in the stomach, liver and small intestine (r2 0.857, 0.956 and 0.946; variation coefficients 6.0%, 3.2% and 6.4%). Laser speckle-contrast visualization, due to the absence of the probe contacting the tissue and due to the ability to investigate large impaired areas in the real-time mode, is a perspective method for intraoperative assessment of the intestinal viability. However, the authors report that respiratory movements strongly affect the data obtained [56]. The benefits of this method include the possibility of performing contactless wide-field measurements of microcirculatory abnormalities in real scale and real time modes [57–60]. The factors decreasing the informativeness of laser speckle-contrasted visualization, are the effects on the registered transmittable pulsation data inflicted by the cardiovascular system and by the mechanical movements of the internal organs [34], as well as the relativity of microcirculation parameters, which affects the objectiveness of the tests conducted.

Side-light dark-field visualization

The method of side-light dark-field visualization includes obtaining contrasted images of biological tissue perfusion due to selective absorption of stroboscopic light with a wave length of 530 nm by hemoglobin molecules in red blood cells [61]. F.J. de Bruin et al. [62] were using the side-light dark field to evaluate the intestinal viability in 17 patients using such microcirculation parameters as the microvascular circulation index, the percentage of perfused vessels, the density of perfused vessels and the total vessel density. The measurements were carried out in each patient using the sublingual area and the serous membrane of the intestine. The authors came to the conclusion that the technology is very promising in terms of visualizing and evaluating the microcirculation in the intestinal wall. C.M. Treu et al. [63] report that this visualization method is cost-effective, safe and very sensitive, which provides obtaining reliable diagnostic data. However, S.M. Jansen et al. [64] report in their research work that the method requires direct contact between the probe and the serous membrane of the intestine, which affects registration due to the effects of interfering factors from the operator's side (hand tremors, uneven probe application pressure) and from the examined object (respiratory movements, transmitted pulsation of the cardiovascular system).

Optical coherent tomography

Optical coherent tomography is a visualization method, which provides information on the cross-section of tissues with high resolution and does not require direct contact with the examined objects. The method is based on the analysis of backward reflected radiation with measuring the delay for the purpose of defining the depth, at which the reflection occurs. The optical coherent tomography uses the near infrared range light. The delay of backward-reflected waves cannot be measured directly, which is why reference measurement is used. When using the interferometer, the part of light is directed to the sample, while the other part — to the reference arm of known length [65]. Y. Tian et al. [66], when performing the experimental research using small laboratory animals, have measured the changes of density, the length and the mean diameter of vessels in various layers of the intestinal wall in the normal conditions and during the ischemia. As a result of the research, significant decrease was registered in the density of vessel perfusion in all the layers of the intestine when exposed to ischemia. The most significantly affected part is the mucosa [66]. The method of registering data using optical coherent tomography requires direct contact between the probe and the serous membrane of the intestine, with this, there are no standardized approaches to sterilizing the equipment of the optical coherent tomography, raising the necessity of using aseptic gaskets between the device and the zone of interest. Optical coherent

tomography, being an operator-dependent method due to the necessity of equipment sensor positioning at the zone of interest by the hand of an operator, is subject to the effect of such factors as the hand tremors, the transmissive pulsation from the major vessels and the respiratory movements of the patient. According to the opinion from S.M. Jansen et al. [67], optical coherent tomography can be implemented for the intraoperative evaluation of intestinal perfusion, but the existing devices require technical rework for enabling their use during surgeries.

Fluorescent spectroscopy

The basis of fluorescent spectroscopy is the assessment of the content of various fluorophores, reflecting the metabolic status of the biological tissues within the wavelength range of 340–370 nm and 450 nm [68–72]. A.A. Zakharenko [73] reports that measuring the fluorescence levels of the oxidative metabolism co-enzyme NADH is promising in the intraoperative evaluation of intestinal perfusion. The main downside of this technology is the required contact between the equipment's optical probe with the examined tissue [74]. However, the use of fluorescent visualization can solve this issue.

ICG-visualization (indocyanine green imaging)

ICG-visualization (indocyanine green imaging) is based on the ability of the staining agent (Indocyanine green) to emit fluorescent signal when being excitated by the light source with a specific wavelength (nearest infrared spectrum — 700–900 nm). The method has gained wide spreading during scheduled and urgent gastrointestinal tract surgeries [75]. K. Nohara et al. [76] in their research work have demonstrated the use of ICG in two patients with strangulation-type intestinal obstruction when evaluating the compromised area of the intestine. Both patients have resolved successfully and with no complications after surgery. The authors have found that fluorescent ICG visualization can be considered a method for making a decision on the intestinal resection-type intervention in patients with strangulation-related intestinal obstruction, however, with the warning that no quantitative evaluations of the fluorescence were carried out and the optimal ICG dosage for the evaluation of intestine is not currently well-defined. Certain difficulties were reported for the macroscopic identification of the fluorescence borders that allow for predicting the viability of the ischemic intestine. The authors note that ICG cannot be used in patients with allergy to iodine-containing medications [76]. Two meta-analyses have found a 70% decrease in the rates of anastomosis insufficiency when using the ICG [77]. The downside of the method is its invasiveness. The literature describes cases of allergic reactions developing when Indocyanine green was used [35]. The important aspect is the absence of quantitative evaluation of signal intensity, which depends on the distance between the intestine and the camera, along with the surgeon's subjective opinion [78].

Infrared thermography

Infrared thermography is based on detecting infrared radiation emitted by the surface of the object. This allows for registering the distribution of thermal fields in the biotissues, developing due to the microcirculatory, metabolic and vegetative activity [79]. Thermography cameras are capable of registering the radiation in the infrared range (0.9–14.0 μm) [80]. The benefits of the method may include its cost-effective implementation, low operating costs, significant comfort and operability. Besides, using the infrared thermography, single evaluations can be performed along with the repeated ones for the purpose of dynamic assessment [81]. Nevertheless, G.J. Tattersall et al. [82] report that this method does not allow for registering minimal thermal changes occurring in cases of inflamed tissues. Besides, a group of authors headed by A. Repež [83] reports that the temperature shift is not always correlating with the intestinal perfusion.

Photoplethysmography

Photoplethysmography is a non-invasive method for measuring the changes in the blood volume in the microcirculation, based on the optical properties, such as absorption, scattering and transmission of certain light wavelengths by the tissues [84]. The absorption and reflection of light by the intestinal wall are influenced by its hemoglobin content and by the total volume of circulating blood. Using the RGB-camera (red, green and blue ranges) allows for registering the shifts of the reflected light resulting due to changes in the blood volume. Among the benefits of this method, of note are the absence of the necessity of using exogenous contrasting reagent, the possibility of constant tracking the circulation in the intestinal wall, the accessibility of the equipment and simultaneous reading of several parameters (blood oxygen saturation, or saturation, SpO_2; heart rate; respiratory rate) [85, 86]. The downside of this method is the time delay required for obtaining the image of the intestinal wall perfusion. Besides,

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the fluctuations in the parameters of central blood circulation and the changes of blood pressure can also add interference to the measured parameters [34]. The use of RGB-camera together with the magnification system and with corresponding image processing algorithms allows for implementing the circulation rate measurements in the capillaries at any spontaneously selected area of the body [87]. Such an approach potentially allows for early detecting various diseases associated with microcirculation abnormalities. The disadvantage of this method also includes its sensitivity to respiration and body movements. Besides, uneven surface of the tissue can hamper the process of obtaining reliable data.

Hyperspectral visualization

Hyperspectral visualization is based on spatial spectrometry using the three-dimensional set of data (hypercube) and representing spatial coordinates in wide and continuous range of electromagnetic spectrum. Hyperspectral visualization allows for measuring the spectral characteristics of every pixel having a spectral curve [88–92]. During the last 5 years, more and more publications were found in the foreign literature, where the method used for assessing the viability of the intestine is the hyperspectral visualization. The method demonstrates high efficiency of analyzing intestinal ischemia with high sensitivity to changes in the microcirculation, especially in the near infrared range of the spectrum [93–95].

Within the premises of the Research and Development Center of Biomedical Photonics under the Federal State Budgetary Educational Institution of Higher Education "Orel State University (named after I.S. Turgenev)", experimental research was performed in rats with evaluating the capabilities provided by the hyperspectral visualization method for analyzing the intestinal ischemia [96]. The trial involved an original developed hyperspectral visualization system, consisting of a broad-band radiation source with the FRI61F50 fiber ring light source (Thorlabs, Inc.) and the Specim IQ hyperspectral camera with the range of 400–1000 nm (Specim, Spectral Imaging Ltd., Finland). The camera has the dimensions of 207×91×74 mm (objective — 125.5 mm), which is comparable to the size of Canon EOS 650D Kit EF-S photo-camera (133×100×79 mm) and which does not create any issues in terms of its mobile use when operating in the surgery room. The time required for evaluating the perfusion of the intestinal wall during the experiment, was not more than 5 minutes, which could not negatively affect the course of the surgical intervention. It was demonstrated that hyperspectral camera allows for obtaining information on the status of the microcirculation in the intestinal wall by examining the saturation of the tissues. Besides, this technology allows for evaluating the oxy-/deoxyhemoglobin and water indexes. Our research has shown that colored dimeric saturation maps compiled when modeling the intestinal ischemia, allow for specifying several SpO_2 intervals corresponding to the morphological changes in the intestinal wall, and thus allowing for judging on the reversibility of the intestinal damage.

CONCLUSION

Each method of assessing the microcirculation in the intestinal wall has its limitations. The intraoperative system intended for supporting the physician's decisions about the viability of the intestinal wall, based on quantitative parameters, is the indispensable element of surgical procedures in cases of intestinal ischemia. The methods of optical spectroscopy and visualization, in particular, hyperspectral visualization, represent the promising non-invasive equipments for assessing the ischemic damage in the intestinal wall, allowing for obtaining a complex information on the microcirculation status of the intestinal wall. However, it is important to define the indications and the place of each objective approach for evaluating the perfusion in the algorithm of intraoperative diagnostics of acute intestinal ischemia.

ADDITIONAL INFORMATION

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AUTHORS' INFO

The author responsible for the correspondence:
Nikita A. Adamenkov;
address: 10 Pobedy blvd, 302028 Orel, Russia;
ORCID: 0000-0002-0238-2941;
eLibrary SPIN: 3348-8250;
e-mail: nikita-ad@mail.ru

Co-authors:
Andrian V. Mamoshin, MD, PhD, Associate Professor;
ORCID: 0000-0003-1787-5156;
eLibrary SPIN: 2553-1200;
e-mail: dr.mamoshin@mail.ru

Viktor V. Dremin, PhD, Associate Professor;
ORCID: 0000-0001-6974-3505;
eLibrary SPIN: 8990-5396;
e-mail: dremin_viktor@mail.ru

Elena V. Potapova, PhD, Associate Professor;
ORCID: 0000-0002-9227-6308;
eLibrary SPIN: 9315-8770;
e-mail: potapova_ev_ogu@mail.ru

Valery V. Shupletsov;
ORCID: 0009-0006-0024-8518;
eLibrary SPIN: 5964-9055;
e-mail: valery.shupletsov@bmecenter.ru

ОБ АВТОРАХ

Автор, ответственный за переписку:
Адаменков Никита Алексеевич;
адрес: Россия, 302028, Орёл, б-р Победы, д. 10;
ORCID: 0000-0002-0238-2941;
eLibrary SPIN: 3348-8250;
e-mail: nikita-ad@mail.ru

Соавторы:
Мамошин Андриан Валерьевич, д-р мед. наук, доцент;
ORCID: 0000-0003-1787-5156;
eLibrary SPIN: 2553-1200;
e-mail: dr.mamoshin@mail.ru

Дрёмин Виктор Владимирович, канд. техн. наук, доцент;
ORCID: 0000-0001-6974-3505;
eLibrary SPIN: 8990-5396;
e-mail: dremin_viktor@mail.ru

Потапова Елена Владимировна, канд. техн. наук, доцент;
ORCID: 0000-0002-9227-6308;
eLibrary SPIN: 9315-8770;
e-mail: potapova_ev_ogu@mail.ru

Шуплецов Валерий Витальевич;
ORCID: 0009-0006-0024-8518;
eLibrary SPIN: 5964-9055;
e-mail: valery.shupletsov@bmecenter.ru

Yuri V. Ivanov, MD, PhD, Professor;
ORCID: 0000-0001-6209-4194;
eLibrary SPIN: 3240-4335;
e-mail: ivanovkb83@yandex.ru

Dmitry N. Panchenkov, MD, PhD, Professor;
ORCID: 0000-0001-8539-4392;
eLibrary SPIN: 4316-4651;
e-mail: dnpanchenkov@mail.ru

Andrey V. Dunaev, PhD, Associate Professor;
ORCID: 0000-0003-4431-6288;
eLibrary SPIN: 8128-3093;
e-mail: dunaev@bmecenter.ru

Иванов Юрий Викторович, д-р мед. наук, профессор;
ORCID: 0000-0001-6209-4194;
eLibrary SPIN: 3240-4335;
e-mail: ivanovkb83@yandex.ru

Панченков Дмитрий Николаевич, д-р мед. наук, профессор;
ORCID: 0000-0001-8539-4392;
eLibrary SPIN: 4316-4651;
e-mail: dnpanchenkov@mail.ru

Дунаев Андрей Валерьевич, д-р техн. наук, доцент;
ORCID: 0000-0003-4431-6288;
eLibrary SPIN: 8128-3093;
e-mail: dunaev@bmecenter.ru

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