Experimental study

Experimental determination of threshold voltage for retinal high-frequency electric welding using a 25-G original unipolar probe depending on the vitreous cavity content

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Експериментальне визначення порогових параметрів напруги електричного струму при високочастотному електрозварюванні сітківки оригінальним монополярним зондом 25-G в залежності від вмісту вітреальної порожнини

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Abstract

Purpose: *To determine experimentally the threshold voltage for retinal high-frequency electric welding (HFEW) using a 25-gauge original unipolar welding probe depending on the content of the vitreous cavity and justify the results theoretically by finite element modeling (FEM).*

Material and Methods: *The experiment involved three rabbits (6 eyes; two experimental rabbits and one control rabbit). Retinal HFEW was performed in eyes filled with perfluorodecalin (PFD) or air in the experimental group and intact vitreous body in the control group. FEM was used for simulating the effects of retinal heating with electric current.*

Results: *In the experimental study, the threshold voltage for retinal HFEW was 11 V, 12 V and 12 V in the presence of the vitreous, PFD and air, respectively. Findings of the FEM of the electric current flow through the tissue (10.8 V for the vitreous, 11.5 V for the air and 12 V for PFD) confirmed the experimental results. Other HFEW settings (current frequency, 66 kHz; current, 0.3A; exposure duration, 1 s) were not changed throughout the experiment. The difference in the threshold voltage for HFEW of the retina can be explained by a relatively high conductivity of the vitreous, while PFD and air are dielectrics.*

Conclusion: *The threshold voltage for retinal HFEW using a 25-gauge original unipolar welding probe was 11 V, 12 V and 12 V in the presence of the vitreous, air and PFD in the vitreous cavity, respectively, which was confirmed by FEM simulations.*

Keywords: *retina, high-frequency welding of biological tissues, retinopexy, welding probe, threshold voltage, finite-element modeling, perfluorodecalin, air.*

Резюме

Мета. *Визначити в експерименті порогові параметри напруги електричного струму при застосуванні високочастотного (66 кГц) електрозварювання сітківки оригінальним монополярним зварювальним зон-*

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дом 25-G калібру в залежності від вмісту вітреальної порожнини (склоподібне тіло, повітря та перфтордекалін), а також обґрунтувати ці параметри за допомогою кінцево-елементного моделювання.

Матеріал та методи. *Три кролика (6 очей) були використані в експерименті: експериментальна (2 кролика, 4 ока) та контрольна групи (1 кролик, 2 ока). У експериментальній групі проводилося ВЕБТ сітківки струмом за тампонади перфтордекаліном або повітрям. У контрольній групі виконувалося ВЕБТ сітківки струмом за наявності склоподібного тіла. Для математичного моделювання електронагрівання сітківки використовувався метод кінцевих елементів.*

Результати. *Експериментально за наявності склоподібного тіла, перфтордекаліну та стерильного повітря порогова напруга ВЕБТ сітківки становила 11 В, 12 В та 12 В відповідно. Кінцево-елементне моделювання протікання електричного струму підтвердило експериментальні дані: 10,8 В для склоподібного тіла, 11,5 В для повітря і 12 В для перфтордекаліну. Інші параметри (частота струму — 66 кГц, сила струму — 0,3 А, експозиція — 1 с) були постійними. Різниця порогових напруг ВЕБТ обумовлена відносно високою електропровідністю склоподібного тіла, в той час як перфтордекалін та повітря є діелектриками.*

Висновки. *Порогові значення напруги ВЕБТ сітківки під час використання оригінального монополярного зварювального зонда калібру 25-G становили 11 В для склоподібного тіла, 12 В для повітря та 12 В для перфтордекаліну, що підтвердилося результатами кінцево-елементного моделювання.*

Ключові слова: *сітківка, високочастотне електрозварювання біологічних тканин, ретинопексія, зварювальний зонд, порогові параметри напруги струму, кінцево-елементне моделювання, перфтордекалін, стерильне повітря.*

Introduction

Rhegmatogenous retinal detachment (RRD) results in significantly decreased visual acuity and working capacity if untimely and/or ineffectively treated. RRD incidence is 6.3–17.9 cases per 100 000 population, depending on the reporting sources [1, 2]. One of the issues of RRD repair is RRD recurrence. The rate of RRD recurrence after successful primary repair varies widely from 6 % to 39.8 % in the literature [2-4]. A relatively high RRD recurrence rate may be associated with missed or poorly sealed retinal breaks, remaining traction, development of proliferative vitreoretinopathy and no long-term tamponade. Another factor predisposing to RRD recurrence is poor retinopexy [5].

Laser retinopexy leads to strong chorioretinal adhesion only in up to 3–4 weeks [5, 6]. This is a substantial shortcoming of the conventional treatment, given a relatively high incidence of postoperative RRD recurrence and the need for long-term gas or silicone oil endotamponade while a strong chorioretinal adhesion is formed. These shortcomings have led to a search for more effective retinopexy techniques such as high-frequency electric welding (HFEW). The HFEW technique, developed in the Filatov Institute of Eye Diseases and Tissue Therapy of the National Academy of Sciences of Ukraine and the Paton Electric Welding Institute using a 20-G welding probe and a special generator, was introduced in vitreoretinal surgery by Pasyechnikova and Umanets [5, 7, 8]. Later, Saud and Serhiienko [9] developed a 23-G unipolar welding probe for suprachoroidal HFEW, showing its effectiveness.

Previous studies demonstrated that electrothermal adhesion (which is the aim and consequence of HFEW) using a 20-gauge welding probe generated firmer and faster chorioretinal adhesion than that achieved by laser retinopexy [10], which was a pre-requisite for the current study. Another important point is that electrothermal adhesion allows a surgeon to avoid long-term endotamponade in 30% of cases [11].

Moreover, there is an increasing trend towards minimally invasive interventions with small-caliber instruments in vitreoretinal surgery. Indeed, most current instruments for minimally invasive vitrectomy are 23-, 25- and sometimes 27-gauge instruments. Therefore, the disadvantages of laser retinopexy, a clear trend in vitreoretinal surgery towards minimal invasiveness and the problem of recurrent RRD create a need for alternative small-gauge retinopexy techniques (e.g., HFEW retinopexy). Furthermore, determining the threshold voltage parameters and justifying them by mathematical modeling are critically important for enabling controllable electrothermal effects on retinal structures without damage to the latter during surgical intervention, considering the physical properties of the content of the vitreous cavity.

The purpose of this study was (1) to determine experimentally the threshold voltage parameters for high-frequency (66 kHz) electric welding of the retina using a 25-gauge original unipolar welding probe depending on the content of the vitreous cavity (the vitreous, air or perfluorodecalin [PFD]) and (2) to justify these parameters using finite element modeling (FEM).

Material and Methods

Three healthy Chinchilla rabbits (6 eyes; two experimental rabbits and one control rabbit) of 2.5–3.5 kg were used in the experimental study. Experimental rabbits underwent closed pars plana vitrectomy (PPV) using Accurus 800 CS vitrectomy system (Alcon Laboratories Inc., Fort Worth, TX). One port was used for irrigation, and two other ports were utilized as entry points for the endoilluminator and vitreous cutter. After vitrectomy, sterile air was used to fill the vitreous cavity of the right eye, whereas PFD used to fill the vitreous cavity of the left eye. Subsequently, HFEW was performed at 66 kHz using the 25-gauge original unipolar welding probe in the presence

of air endotamponade (two right eyes) or PFD endotamponade (two left eyes). In the control animal, no vitrectomy was performed, and HFEW was conducted bilaterally in the presence of the vitreous.

A modified generator EK-300 M1 and the 25-gauge unipolar welding probe (developed in collaboration of the Filatov Institute and the Paton Electric Welding Institute) were employed for retinal HFEW as described previously [8, 12]. The welding probe consists of (1) a copper pin that is insulated with a sheath and placed inside a 25-gauge metal tube and (2) a 27-gauge gold-sphere electrode attached to the probe end, representing the surface via which the probe interacts with the retina.

During the experiment, five HFEW burns were applied beneath the optic disc (placed 0.5-disc diameter apart) at HFEW voltages of 11 V, 12 V, 13 V and 14 V. Other HFEW settings (current frequency, 66 kHz; current, 0.3 A; exposure duration, 1 s) were not changed throughout the experiment. HFEW-associated macroscopic retinal changes were evaluated ophthalmoscopically. iPhone 12 Pro and 30-D lens were used for taking fundus photographs.

The threshold voltage parameters of high-frequency (66-kHz) current were considered those that caused certain ophthalmoscopic retinal changes — ring-shaped retinal graying within the diameter of the probe with no retinal break. Taking into account the optical properties of the intraocular environment (the vitreous, air and PFD), these changes, when possible, were confirmed by the optical coherence tomography (OCT) that showed minimal retinal damage (with preserved retinal layer differentiation and inner retinal edema) and were in agreement with the findings of previous studies using a 20-gauge welding probe [5]. This study did not aim to assess the efficacy of retinopexy, which will be addressed by further research.

As a non-invasive technique for assessing retinal anatomy, HFEW spots were evaluated by OCT (REVO FC; Optopol Technology, Zawiercie, Poland) immediately after surgery. Specifically, retinal changes were assessed at HFEW sites created using different voltage parameters.

Mathematical modeling of electrothermal heating of the retina and surrounding tissues was conducted to justify the experimental findings. Modeling was performed by solving the set of partial differential equations for bioheating transfer and electrical conductivity using the COMSOL Multiphysics package. The equations used, boundary conditions, model geometry and other modeling details were described previously [13], and the modeling reported in this study differs only in the diameter of the tip of the welding probe.

All animal experiments were performed in compliance with the Law of Ukraine on Protection of Animals from Cruel Treatment No. 3447-IV dated 21.02.2006 and European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes from the European Treaty Series (Strasbourg, 1986) and approved by the Bioethics Committee of the Filatov Institute (protocol No. 3 of September 12, 2024).

Results

In the eyes of the control rabbit, the application of HFEW spots to the retina at 11 V resulted in local retinal graying shaped as a ring with a diameter not larger than that of the probe. Additionally, the application of HFEW spots to the retina at 12 V or 13 V caused more marked changes in the form of ring-shaped whitish discoloration of the retina (these changes were more pronounced at 13 V than at 12 V). Moreover, the application of HFEW spots to the retina at 14 V resulted in marked coagulative changes with retinal whitening shaped as a ring (with a diameter larger than that of the probe) and a retinal break at the center of the application site. Figure 1 shows the changes described above that occurred immediately after applying HFEW spots to the retina.

In the eyes of experimental rabbits, in the presence of air tamponade, the application of HFEW spots to the retina at 11 V resulted in subtle local retinal graying shaped as a ring with a diameter smaller than that of the welding probe (about 0.8 diameter of the welding probe). Additionally, the application of HFEW spots to the retina at 12 V caused local retinal greying shaped as a ring with a diameter not larger than that of the probe, and the application of HFEW spots to the retina at 13 V resulted in more marked changes (ring-shaped retinal whitening). Moreover, the application of HFEW spots to the retina at 14 V resulted in marked retinal coagulation with a diameter about 1.5 times larger than that of the welding probe, retinal whitening and a retinal break at the center of the application site.

In the presence of PFD tamponade, the application of HFEW spots to the retina at 11 V resulted in subtle local retinal graying shaped as a ring with a diameter smaller

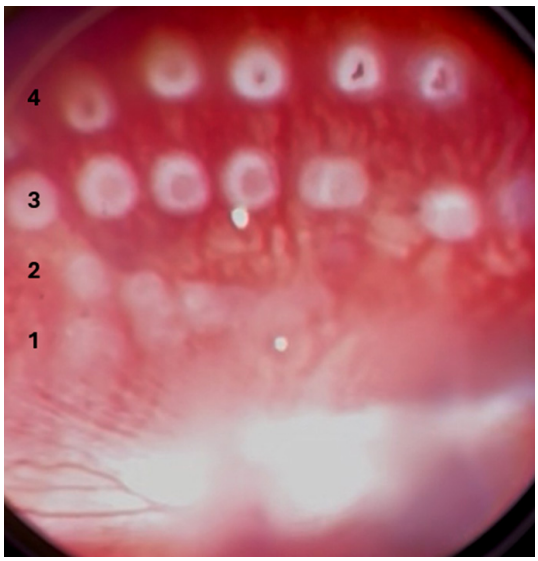

Fig. 1. Ophthalmoscopic picture after retinal high-frequency electric welding (HFEW) in the presence of the vitreous. Note the effects of 11-V HFEW (bottom row, 1) to 14-V HFEW (top row, 4). Marked retinal coagulative changes (retinal whitening) with the formation of retinal breaks at the center of the application site appear with an increase in HFEW voltage.

than that of the welding probe (about 0.8 diameter of the welding probe). Additionally, the application of HFEW spots to the retina at 12 V or 13 V led to more marked changes in the form of ring-shaped local retinal whitening (these changes were more pronounced at 13 V than at 12 V). Moreover, the application of HFEW spots to the retina at 14 V resulted in marked coagulative changes with retinal whitening shaped as a ring (with a diameter about 1.5 times larger than that of the probe) and a retinal break at the center of the application site.

OCT of the sites of HFEW application was performed within an hour after the experiment. It was not possible to obtain interpretable OCT findings in eyes with PFD or air tamponade, given the difference in refractive indices between tamponade agents; therefore, we analyzed OCT images of the retinal sites of HFEW application only in the control eyes with intact vitreous.

The retinal sites of HFEW application at 11 V were characterized by retinal edema (especially, that of the inner retinal layers), with mildly increased hyperreflectivity and preserved differentiation of retinal layers (Fig. 2A1 – A2). Additionally, the retinal sites of HFEW application at 12 V appeared as hyperreflective foci with substantial retinal changes and retinal layers that could not be differentiated from each other (Fig. 2B). Moreover, the retinal sites of HFEW application at 13 V or 14 V were characterized by marked coagulative changes (intense hyperreflective foci) with a retinal defect (a retinal break) in the center of HFEW application (Fig. 2C).

FEM of electrothermal heating of the retina and surrounding tissues was conducted to explain the experimental findings. The main task of the modeling was to determine threshold voltages for retinal HFEW depending on the content of the vitreous cavity. Threshold voltages were determined taking into account the following considerations. The temperature of the coagulation of retinal proteins (TCOAG) is about 50ºC [14, 15], and HFEW exposure time (t) is 1 s. Therefore, while simulating an increase in temperature with time at retinal HFEW sites for various voltages, it is required to determine the threshold voltage U_{THR} at which the retinal heating temperature reaches 50ºC in 1 s after the current has been switched on. Figure 3C shows the increase in temperature with time at retinal HFEW sites at three voltage values close to U_{THR} for air endotamponade. We can see that the condition of reaching a temperature (T) of approximately 50ºC during 1 s is best fulfilled at a voltage (U) of 11.5 V, with the increase in temperature with time substantially different from those at other voltages that differ by just 0.5 V from 11.5 V. Therefore, we found that U_{THR} = 11.5 V for air endotamponade.

We found threshold voltages for PFD endotamponade (U_{THR} = 12 V; Fig. 3B) and preserved vitreous (U_{THR} = 10.8 V; Fig. 3A) in a way similar to that described above. These results were in fair agreement with the experimental findings. Operating parameters were considered those that can be set on the control panel of the welding generator, given that the voltage parameters cannot be set lower than whole numbers of Volts in the experiment and the parameters determined by FEM were closely similar to those determined experimentally.

Discussion

Electrosurgery is a rather common technique for fusing biological tissues [16]. As a main distinguishing feature of this method, high-frequency electrical current passes through the tissue to achieve its heating, whereas in electric tissue coagulation, the tissue is heated directly by the active electrode, with direct heat transfer from the electrode and tissue coagulation [16]. Previous experiments have demonstrated that HFEW causes the electrical breakdown of cellular membranes develops without cell destruction (at an optimal frequency of 66 kHz), leading to bonding of biological tissues with minimum structural damage that is induced by electrothermal denaturation of proteins [17, 18]. Such an effect can be reached when tissue resistance is substantially reduced and tissue temperature is increased to 50° – 70°C, which is a precondition for protein denaturation with a minimum structural damage [14, 15]. Moreover, this process is accompanied by the formation of an adhesive substrate of denatured collagen and other molecules of the extracellular matrix [5, 10, 19]. Along with the denaturation of proteins in the outer part of the plasmalemma, it is this substrate that causes fast chorioretinal adhesion after retinal exposure to HFEW [5,

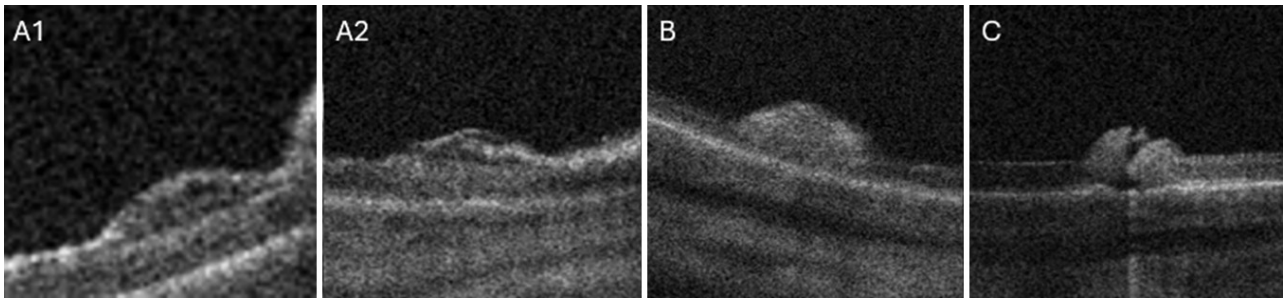

Fig. 2. Optical coherence tomography photographs of retinal high-frequency electric welding (HFEW) application sites at a voltage of 11 V (A1 and A2), 12 V (B) and 13 V or 14 V (C). The HFEW application sites at a voltage of 11 V (panel A) are characterized by retinal edema with mildly increased hyperreflectivity and the preserved structure of retinal layers. The HFEW application sites at a voltage of 12 V (panel B) and 13 V or 14 V (panel C) resulted in marked coagulative changes (intense hyperreflective foci) with a retinal break in the center of the site (panel C).

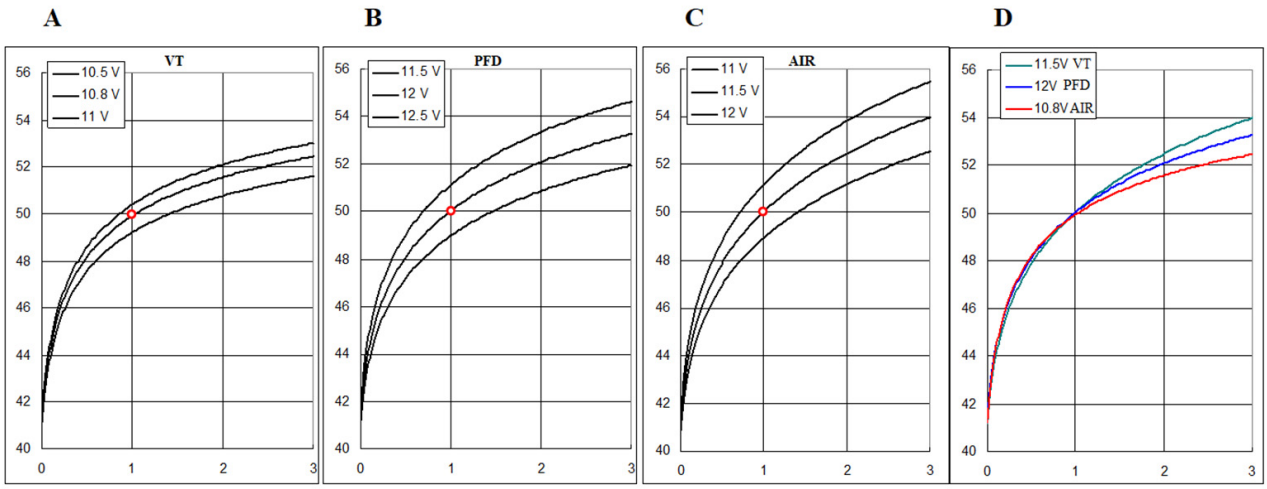

Fig. 3. Increases in retinal temperature with time during retinal high-frequency electric welding (HFEW) at three different voltages (specified on particular diagrams) with the vitreous (VT; A), perfluorodecalin tamponade (PFD; B) or air tamponade (C), and the comparative diagram of optimal voltage values for VT, PFD and air. The increases in retinal temperature with time during retinal HFEW for the three vitreous cavity filling variants were calculated for threshold HFEW voltages.

10, 19]. Immediately after retinal HFEW, the inner retinal layers at the site of retinal contact with the welding probe are more damaged than the outer retinal layers, which was confirmed by previous studies using morphological and OCT evidence [5], as well as this study. It is likely that this is the consequence of using this method, resulting in a higher temperature at the site of retinal contact with the welding probe than at the site of the outer retina.

Recent advances in vitreoretinal surgery have resulted in an increased use of minimally invasive small-caliber instruments (including 25- and 27-gauge tools) for improved intraoperative fluidic stability, tissue stability and accuracy of manipulations [20]. Furthermore, 25-gauge vitrectomy offers both adequate fluidic/tissue stability and instrument performance/rigidity, which are the most preferrable characteristics for such surgery, representing the preferred choice for the majority of cases [20]. However, 27-gauge instruments might be characterized by longer surgical time and low instrument rigidity, although these data are inconsistent [20, 21]. That is why it is reasonable to shift away from more invasive 20-G and 23-G instruments in favor of the development, experimental testing and validation of small caliber instruments (particularly, 25-G instruments).

Therefore, previous studies have demonstrated that electrothermal adhesion–assisted HFEW retinopexy (using a 20-G welding probe) generated firmer and faster chorioretinal adhesion, which was a pre-requisite for the current study. However, vitreoretinal surgery is evolving towards minimally invasive interventions with small caliber instruments. Hence, using small caliber instruments for electrothermal chorioretinal adhesion in RRD could improve surgical outcomes, partially due to the advantages of minimal invasive vitrectomy.

Building on previous studies for the 20-gauge welding probe, we had to clarify threshold values for HFEW voltages for the novel 25-gauge original unipolar welding probe. Previously, we determined the optimal voltage parameters for HFEW retinopexy during vitrectomy using the 20-gauge unipolar welding probe in the presence of the vitreous, PFD tamponade or air tamponade [13]. Optimal voltage parameters for HFEW retinopexy depended on the tamponade agent (the vitreous, PFD or air) [13]. Taking into account that coagulation occurs only at the sites where the temperature exceeds a critical value, the dynamics of the thermal effects on the retina during HFEW, depending on the tamponade agent, can be investigated via mathematical modeling that considers only the heat transfer and tissue heating while the electric current passes through the tissue.

Taking into account the change-over in the probe diameter, it had been also expected that the probe with the smaller diameter would require a lower voltage, which was experimentally demonstrated in rabbit eyes. In the presence of the vitreous, the threshold voltage for thermoelectrical adhesion for the 25-G unipolar welding probe (10.8 V) was substantially lower than that for the 20-G unipolar welding probe (15.5 V) [13]. The use of higher HFEW voltages (close to those optimal for the 20-G unipolar welding probe) with the 25-G unipolar welding probe resulted in more severe coagulation changes with a retinal break in the experimental rabbit eye. This also confirms the need to determine threshold parameters for the use of probes of various calibers.

FEM could explain the decrease in threshold HFEW voltages with a reduction in the caliber of the probe. Figures 4A and 4B show the distributions of temperatures at the probe tip for the model of the eye filled with the vitreous for 25-G and 20-G probes, respectively, computed for threshold voltages U_{THR} of 10.8 V and 15.5 V, respectively, in 1 s after the current has been switched on. For the 25-G probe, heating to the target temperature was more homogeneous and achieved at a lower HFEW voltage. This can be explained by the fact that a reduction (by about half) in the caliber and diameter of the probe resulted in a sub-

stantial (as much as a four times) increase in the current density in and close to the margins of the probe, with no change in supply voltage or current. Because the power of dissipated heat is proportional to the square of current density, the heat dissipated close to the margins of the probe (where there is maximum current density) increased more than elsewhere. Consequently, reaching the operating values of current density requires applying substantially lower threshold voltage at which the current density at the site of maximum heating for the 25-G probe will be practically the same than that for the 20-G probe (Figures 4C and 4D).

OCT images of the chorioretinal complex demonstrated anatomical changes after the exposure to retinal HFEW (66 kHz) using the 25-G original unipolar welding probe. OCT images for the 25-G unipolar welding probe (Fig. 2) were similar to those for the 20-G original unipolar welding probe [5, 8]. Optimal changes in the chorioretinal complex occurred after exposure to HFEW at experimentally and theoretically determined voltage. Such changes were accompanied by increased retinal reflectivity with the preservation of retinal layer differentiation, and possible edema of the inner retinal layers immediately after HFEW (Fig. 2A). Higher HFEW voltages resulted in marked coagulative changes with ultrastructural retinal destruction and formation of retinal breaks (Figs 2A and 2B).

This experimental study used the 25-G probe and confirmed the finding of our previous study [13] using the 20-G probe: the HFEW voltage required to cause coagulative changes without ultrastructural retinal destruction depends on the tamponade agent. The HFEW threshold voltage required to cause coagulative changes without retinal ultrastructural destruction was higher for PFD or air tamponade than for the vitreous. This finding was explained using FEM. PFD and air are dielectrics and have low high-frequency conductivity, whereas the vitreous has rather high high-frequency conductivity [22]. The modeling showed that during retinal HFEW in the presence of the vitreous, the latter also conducts the electric current (Fig. 5A) and is heated, which decreases the voltage required for the same result (anatomical changes and for-

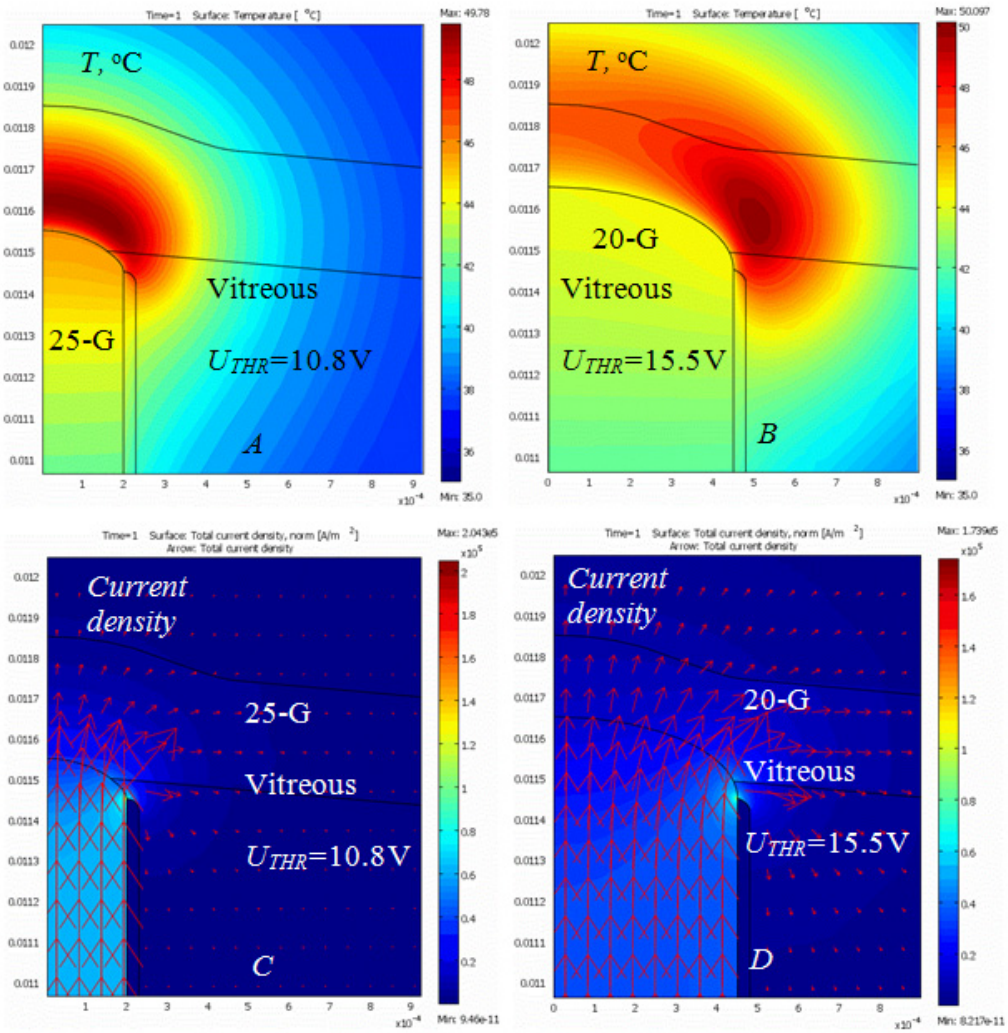

Fig. 4. Temperature distribution (A, B) and current-density distribution (C, D) at the probe tip 1 s after the current has been switched on for the model of an eye with the preserved vitreous. A and C are related to a 25-G probe at a threshold voltage (U_{THR}) of 10.8 V, whereas B and D to a 20-G probe at U_{THR} of 15.5 V.

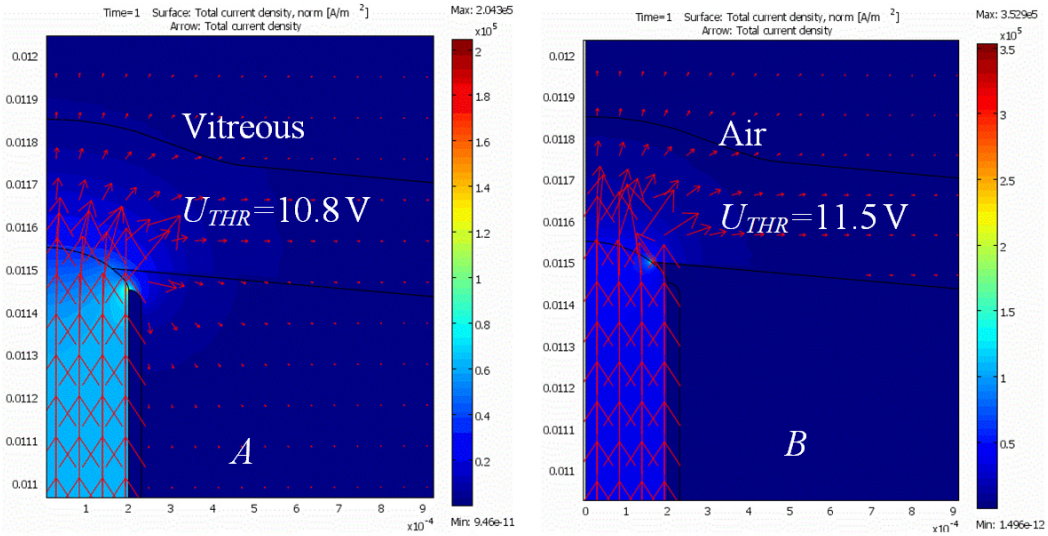

Fig. 5. Current-density distribution at the probe tip for the model of an eye with the preserved vitreous at a threshold voltage (U_{THR}) of 10.8 V (A) and air at U_{THR} of 11.5 V (B).

mation of the chorioretinal adhesion; U_{THR} = 10.8 V). In PFD or air tamponade, the electric current passes through the retina only (Fig. 5B) without additional heating occurs; thus, a higher HFEW voltage is required (12 V and 11.5 V, respectively). Our experimental findings show excellent agreement with the results of FEM, indicating that the selected model is adequate and can accurately justify values of the electric current parameters (voltages) for manipulations required.

A limitation of this study was a small sample of animals. Another limitation was that this was an animal-only study, which may limit the translation of findings to the clinical setting. Although the sample of experimental animals was small, the study purpose was to determine threshold parameters for using a small-caliber welding probe and experimentally test and validate them, which had been performed previously using a larger-caliber probe [13], with those previous findings used as a reference for planning and conducting the current study. An additional limitation was the absence of OCT visualization of chorioretinal changes in animal eyes with air or PFD tamponade due to the physical properties of these substances and difficulties in obtaining interpretable OCT findings. Therefore, this study assumes that, in animal eyes with PFD or air endotamponade, the structural changes after retinal HFEW corresponded to those in eyes in the presence of the vitreous based on previous findings for the larger-caliber (20-G) probe [5, 13]. Our findings are important for further research of chorioretinal anatomical changes in rabbits at different time points after retinal HFEW, taking in account the calculated threshold voltages. Further research may allow justifying the use of the 25-G unipolar welding probe in patients with RRD.

Conclusion

In the experimental study, the threshold voltage for retinal HFEW using the 25-G original unipolar welding probe was 11 V for the vitreous and 12 V for the air or PFD tamponade. These findings were based on ophthalmoscopy (ring-shaped retinal graying within the diameter of the probe) and OCT images (retinal edema with mildly increased hyperreflectivity and preserved differentiation of retinal layers) and were very close to the findings of FEM for electric heating of the retina (10.8 V for the vitreous, 11.5 V for air tamponade and 12 V for PFD tamponade). Further research should assess the potential of using the determined parameters to achieve safe and effective HFEW retinopexy.

Author Contributions

IChumakov E.A. – methodology, writing – preparation of the initial draft, reviewing and editing, visualization, observation; Umanets M.M. – methodology, project administration; Ptashchenko F.O. – methodology, software, visualization. All authors read and approved the final version of the manuscript.

Disclaimers

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Conflict of Interest

The authors declare that they have no conflicts of interest related to this work.

Disclaimer

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Ethical approval

The experiment was conducted in compliance with safety measures, ethical attitude and rules for working with experimental animals in accordance with the “European Convention

for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes" (Strasbourg, 1986) and the Law of Ukraine No. 3447-IV "On the Protection of Animals from Cruelty". The study was approved by the Medical Ethics Committee of the SI "Filatov Institute of Eye Diseases and Tissue Therapy of the National Academy of Medical Sciences of Ukraine" (No. 3 dated 12.09.2024).

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request. Due to institutional policy and patient confidentiality, raw data are not publicly available.

Abbreviations

RDD – rhegmatogenous retinal detachment, HFEW – high-frequency electrical welding of biological tissues, OCT – optical coherence tomometry.

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