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Modern aspects of using of ultrasonic energy in cataract and vitreoretinal surgery

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The review demonstrates current data on the nature of ultrasound, its effect on biological structures and the possibilities of using ultrasound for the diagnosis, conservative and surgical treatment of eye diseases. The article contains descriptions of technologies of cataract surgery using ultrasonic energy, as well as new possibilities of using ultrasound not only to remove the nucleus, but also to remove the cortex of the lens, and modern applications of the energy of ultrasound in vitreoretinal surgery.

Key words:
ultrasound, phacoemulsification, ultrasonic aspiration of cortex, ultrasonic vitrectomy, vitreoretinal surgery

Ultrasound and its properties

Ultrasound (US) is elastic mechanical acoustic waves propagating in various environments (solid, liquid, gaseous). The boundaries of ultrasound are in the range from 15–20 kHz (lower boundary) to 1 GHz (upper boundary). Both boundaries are rather uncertain and beyond human hearing [1, 2].

Ultrasonic waves make intense oscillatory movements with high accelerations during the passage through biological environment. Such an influence on the structure of biological tissues leads to various effects: mechanical, thermal, physico-chemical [1, 2].

The influence of ultrasonic waves on biological objects and tissues is also associated with cavitation. Cavitation is a process of formation of vapor-filled cavities in a liquid environment [1]. The cavitation process is local and does not spread in the environment.

It is possible that the chemical effect of cavitation is due to the formation of electric microcharges on the walls of the cavitation bubbles, followed by electronic breakdown. However, many experimental facts cannot be explained in the frame of this concept. Many chemical reactions under the ultrasound influence occur in aqueous solutions. At high temperatures, water molecules in the cavitation bubble turn to excited state and split into H +, OH– radicals, and are possibly ionized with formation of hydrated electrons. So, nitrogen oxides and hydrogen peroxide are formed under the influence of ultrasound on water in which air is dissolved. In addition, the passage of ultrasound through several substances accelerates the progress of certain chemical reactions. Reactions occurring in the presence of H2O2 and H+ and, especially, oxidative reactions under the influence of atomic oxygen are usually accelerated [1].

In addition to the chemical effect, ultrasound has different mechanical effects on biological objects and tissues. Vibrations of particles of the biological environment, occurring at low intensities (up to 2–3 W/cm2) at frequencies of 105–106 Hz of ultrasound, produce micromassage of tissue elements, which contributes to a better metabolism [3, 4].

During the propagation of ultrasound in any biological environment, the absorption of ultrasound waves and the conversion of acoustic energy into heat energy usually takes place.

Characteristically, the formation of heat does not occur throughout all of the tissue thickness, but manifests itself most noticeably at the boundaries of environments with different wave impedances. Thus, significant heating of biological tissues and their destruction can occur during a considerable increase in the intensity and duration of ultrasound exposure [1, 3, 4].

The use of ultrasound for therapeutic and diagnostic purposes has found application in many branches of medicine [5, 6]. High-frequency ultrasound (107–109 Hz) is used for ultrasound diagnostics, mid-frequency (105–107 Hz) is used in diagnostics and physiotherapy with a thermal effect, and low-frequency (1,5×104–105 Hz) is used in surgery [1, 2].

The use of ultrasound in ophthalmology

Ultrasound has been actively introduced in ophthalmic practice since the 50s of the 20th century [7, 8]. The first application of ultrasound took place in the conservative treatment of pathology of the cornea, optic nerve and vitreous body. The use of ultrasonic energy contributed to the reduction of inflammatory processes and acceleration of tissue repair [2, 9]. At the same time, experimental work was carried out to study the diagnostic capabilities of ultrasound. In 1956, an intraocular tumor was first detected using A-scan ultrasound [7]. Then, methods for 2D and 3D visualization, color Doppler mapping were developed and proposed, each of them has been used up to the present day [2, 8, 10-16].

In surgical practice there are two main directions of ultrasound application. One of them is the use of a concentrated ultrasonic beam to provide a local destructive effect on deep tissues of the body without violating the integrity of surface structures. The second is instrumental ultrasonic surgery, which is most widely used [1, 2].

Ultrasound in cataract surgery

In 1967 the US ophthalmologist C. Kelman first offered the use of low-frequency ultrasound for cataract removal. Ultrasonic machine, offered by him, included an electronic ultrasonic energy generator unit and a nickel piezoelectric transducer with changeable needles and with channels for irrigation and aspiration. It made it possible to remove cataract through small incision [17, 18]. This technique became the basis for the development of ultrasound cataract surgery and has since undergone many changes and improvements.

It is necessary to say a few words about the factors providing the effect of destruction of the lens under the influence of ultrasound. First of all, it is a mechanical effect due to the impact of a moving phaco tip on the lens material [19, 20]. The second factor is the formation of small bubbles while using ultrasound in a liquid environment. The collapse of the bubbles is accompanied by the release of energy, the so-called cavitation phenomenon [20, 21].

The method proposed by C. Kelman was improved in the context of safety of the process of destruction and removal of the lens nucleus. The first ultrasonic phacoemulsification machines were based on longitudinal ultrasonic vibrations. The working part of the instrument was a titanium tip, which made quick forward and backward movements on ultrasonic frequencies and allowed to emulsify the lens nucleus. The use of longitudinal ultrasound had several disadvantages, one of which was the repulsion of lens fragments from the phaco tip [22]. Loss of occlusion forces a surgeon to perform additional manipulations in the anterior chamber, which can lead to mechanical damage of the cornea, Zinn zonules and posterior capsule. When this repulsion effect occurs, ultrasonic energy is not used effectively, because of the absence of direct contact between the needle and lens material. Moreover, restoration of the occlusion and contact of the needle with the lens substance requires additional circulation of irrigation fluid which can also negatively affect the intraocular structures, the corneal endothelium in particular [23]. The damaging effect of ultrasound on the endothelium is due to the influence of free radicals formed during cavitation and local thermal exposure. This effect depends on the duration and power of the ultrasound [24-29]. In connection with the features of the longitudinal ultrasound vibrations, mentioned above, attention began to be paid to such an important component of cataract removal process as the followability of an ultrasonic instrument, which determines the ability to hold the lens fragments in field of effective ultrasonic action. Better followability leads to enhanced effectiveness of ultrasonic emulsification of the tissue [29]. In order to optimize the use of ultrasonic energy, various techniques for mechanical nucleus breaking (phaco-chop, divide-and-conquer approaches etc.) and modifications of linear, pulse, hyperpulse, and burst modes of ultrasound were developed [30–37].

Recently, non-longitudinal phacoemulsification became widespread. This principle is to use torsional, transverse ultrasonic vibrations and their various combinations for destruction of the cataract. These modifications allow to reduce repulsion and increase followability and cutting ability of the ultrasonic tip, that's why ultrasonic energy is used more optimally [35]. Russian scientists (Aznabaev B.M. et al) proposed and introduced the use of three-dimensional ultrasound, which allows more efficient use of ultrasonic energy [38].

Along with this, methods for removing cataract without using ultrasound have been developed, such as hydromonitor phacoemulsification, phacoemulsification based on vibrations in the sound range, phacofragmentation based on fast vibrations of the vacuum in the aspiration line, laser cataract extraction using a YAG laser, a low-intensity helium-neon laser [39-43]. However, these methods are not widely used due to various reasons. One of them is low cutting ability, which limits their use in case of dense cataracts. Femtosecond laser-assisted cataract surgery, besides fragmentation of the lens nucleus, makes it possible to perform high-precision corneal incisions and capsulorhexis and to increase the predictability of surgery outcomes [44-46]. However, its application does not allow to avoid the use of ultrasound in most cases. Another limiting factor in the use of femtosecond laser is the high cost of the equipment.

Today ultrasonic phacoemulsification remains the most popular and effective method of cataract surgery, and new generation high-tech devices allow performing surgical interventions through small self-sealing incisions [47]. There is every year increase in the need for cataract surgery all around the world and, at the same time, requirements and expectations for the high functional results and quick recovery after treatment are growing both among the physicians and patients [48].

The aspiration of dense and viscous lens cortex is one of the unsolved problems of cataract surgery [49, 50]. Its removal is associated with additional manipulations with the aspiration and irrigation tips, and in some cases the surgeon has to use the phaco tip. This increases the risk of mechanical damage to intraocular structures, such as the posterior capsule, Zinn zonules and cornea. A new system for cortex removal with the possibility of using of dosed low-power ultrasonic energy was developed and proposed by the authors of this article [49]. The works showed that the use of low-dose ultrasonic energy allows to speed up the aspiration of cortex and makes this process more smooth and safe [49]. The system gives the opportunity to reduce the amount of movements in the anterior chamber aimed at division of lens cortex which reduces the risk of mechanical damage to the posterior capsule. Clinical studies have shown that using the ultrasound system for cortex aspiration is accompanied by less changes in the corneal microarchitectonics in the area of paracentesis [50]. The use of ultrasonic energy does not cause thermal damage to the cornea, because the technology is based low doses and short exposure time of ultrasound [51]. Another positive aspect of the proposed system is the reduction of cortex removal stage during the cataract surgery [49].

Ultrasound in vitreoretinal surgery

Ultrasound has found application not only in cataract, but also in vitreoretinal surgery. L.J. Girard et al. for the first time developed an apparatus that allows to remove both the lens and the vitreous body using a low-frequency ultrasonic oscillations [52]. Russian scientists, who proposed in 1980 to use an ultrasound apparatus for phacoemulsification and vitrectomy, were L.V. Kossovsky, G.E. Stolyarenko et al. [53]. However, there were various reasons why at that time ultrasonic vitrector was not widely used in retinal and vitreous surgery. One of them was the size of ultrasonic tip and high ultrasonic power, the use of which was not safe enough in some situations and might lead to a structure disruption of the retina. Specifically it may cause damage to the photoreceptors and pigment epithelium layers and even more serious complications, such as aspiration of the retina followed by its detachment, the development of vitreous haemorrhage in case of blood vessels or ciliary body damage [2, 54]. Another negative factor was the time limit for the safe use: retrolental ultrasonic vitrectomy should not exceed more than 5 minutes, preretinal - up to 1 minute [2]. Instead of ultrasonic tips, mechanical vitrector came to be used, which had a different mechanism of fragmentation and removal of the vitreous body and was safer to use at that time [2]. In 1972 R. Machemer et al. offered the use of a multifunctional instrument that allowed to mechanically cut and aspirate the vitreous body. [55]. This instrument has been improved and today pneumatic guillotine vitrectomy using instruments of 23 and 25G caliber is the world standard for the surgical treatment of vitreoretinal pathology [56]. But despite this, further research for improvements aimed at reducing the trauma of retinal and vitreous surgery continues and becomes increasingly important. First way to make the surgery less traumatic is reducing the size of the instruments. The caliber of modern pneumatic vitrectors is already reaching its minimum limit, its further reduction seems to be inappropriate, since it will lead to a decrease in the performance. In this regard, the question arose about the possibility of non-mechanical destruction of the vitreous body. Modern advances in science and technology made it possible to create new ultrasonic vitrectors, which differ from the previously proposed by small caliber and safe configuration of the tips. Ultrasonic vitrectomy transforms the vitreous body into an easily removable emulsion, reduces the risk of iatrogenic damage to the retina, in contrast to the guillotine technology, where the vitreous body is removed by alternating aspiration-cut cycles, which cause fluctuations of aspiration flow [57, 58].

Currently, several groups of scientists are working on the introduction of ultrasound into vitreoretinal surgery using 20 and 23G caliber ultrasonic vitrectors [59-61]. Recent studies have shown that the use of ultrasonic energy for vitrectomy with new tip configurations does not cause specific retinal complications [60].

The authors of the article developed and offered the use of a 25G caliber ultrasonic vitrector [57, 62]. Experimental and clinical studies, demonstrating the effectiveness and safety of using this microinvasive ultrasonic vitrectomy system have been subsequently carried out [57, 62]. According to experimental investigations, the performance of an ultrasonic vitrector ranges from 3.72 to 10.13 ml/min, depending on the level of the vacuum. The data obtained exceed the average performance of mechanical guillotine vitrectors (from 1.50 to 2.30 ml/min) and vitrectors with double cut technology (TDC); their performance is up to 4.3 ml/min (25G vitrector) and up to 2.1 ml/min (27G vitrector) [57, 63-65]. It has been proved that the use of an ultrasonic vitrector is thermally safe [66]. Clinical investigations using routine and modern research methods (optical coherence tomography-angiography, microperimetry) also showed good clinical and functional results and the absence of specific retinal complications during ultrasonic vitrectomy [60, 62].

Conclusion

Thus, today the use of ultrasonic energy in ophthalmic surgical practice is not limited only by cataract surgery for lens emulsification. Development of new systems with the possibility of using ultrasound for lens cortex removal and microinvasive ultrasonic vitrectomy allows to open new possibilities of improving effectiveness and safety of eye surgery for achievement of better clinical and functional outcomes.

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