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Design of Elementary Piezoelectric Ultrasonic Radiators for Shock Wave Therapy Machines

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ABSTRACT

This article presents the analysis of requirements and restrictions that arise in the design of elementary piezoelectric ultrasonic radiators for shock wave therapy machines. These elements are the component part of the radiating unit (applicator) made in the form of the phased array consisting of several hundred (from 128 to 1024 pieces) of piezoelectric elements, fixed on a metal base in the form of a segment of the spherical surface. Based on the value of the working frequency, the size of the applicator and conditions of filling the surface, geometric dimensions and shape of elementary emitters are estimated.

Key words: piezoelectric ultrasonic radiator, shock-wave therapy, high intensity focused ultrasound, applicator, phased array, lead zirconate titanate.

1. INTRODUCTION

Ultrasonic waves are widely used in medical practice, according to monograph [1]. Against this background, in the last 15 years, the development of shock-wave therapy (SWT) methods has grown considerably. These methods are based on the application of high intensity focused ultrasound (HIFU) through the shock wave formation in the impact area, which leads to local thermal necrosis of tissues or their mechanical destruction. This method is successfully applied for noninvasive destruction of tumors of various internal organs – uterus, prostate, liver, kidneys, and thyroid gland, as demonstrated in publications [1-4]. Significant success is observed in the application of this method for treatment of essential tremor, as is proven in the paper [5], destruction of intracerebral tumors described in the paper [6], treatment of trigeminal neuralgia, according to paper [7] and chronic neuropathic pains according to paper [8].

For the generation of ultrasound, it is possible to apply a wide range of transducers such as hydrodynamic, electromagnetic, etc. described in the monograph [9]. For today SWT devices using piezoelectric transducers for the generation of waves are the most perspective, as is proven in monographs [10, 11]. Modern piezoelectric SWT machines contain in their radiating unit (applicator) up to several hundred of piezoelectric elements fixed on a parabolic (or spherical) surface that sets the direction for focusing the wave fronts formed by piezoelectric elements in a certain area – a focal spot. Thus, simultaneously radiating a shock wave of small pressure, they altogether create pressure in the focal spot of about 100 MPa, according to monographs [10, 12].

The number of publications related to numerical simulation of processes of generation and propagation of ultrasonic waves in SWT machines is increasing [13-15]. The purpose of this work is to select the material, shape and size of elementary radiators to obtain an optimal configuration of the applicator for SWT machines.

2. RESEARCH OBJECTIVE

The therapeutic effect of ultrasound is usually reduced to heating (up to 85 °C) of the treated area or loosening of tissues, resulting in micro- or macro-destruction. For these purposes, compression waves and shock waves are used. Apparatuses generating radial compression waves already have become a daily practice of doctors of various specialties. On the other hand, the action of shock waves can lead to different types of deformation of tissues and changes in their properties. In both cases, it is necessary to strictly localize the area of exposure to radiation in order to prevent damage to adjacent areas of living tissue. In other words, it is necessary to ensure a high specific concentration of energy in the focal spot in a short period without the formation of secondary focuses.

The geometrical shape of this spot is close to spherical with the characteristic size of 1-10 mm. Many therapeutic tasks require the treatment of large areas of tissue within the order of 40-60 mm and, therefore, it is necessary to continuously move the focal spot of the ultrasonic radiator (applicator). Piezoelectric transducers with lenses can be used as focusing devices. They are the least practical because about 40% of the energy, according to monograph [2] is absorbed in the lens. Overheating and damaging the lenses is especially important at high frequencies and intensities of ultrasound. Sound aberrations on the lens also prevent the radiation from focusing.

The second type of radiators is devices containing the piezoelectric ceramic element in the form of parabolic plate, the radiation of which is already focused, according to monograph [15]. In this design, the change of focus position along the axis of the radiator is performed by moving the ceramic inside the device and ranges from 0 to 55 mm. The disadvantage of these radiators is the need to mechanically change the focus position by means of moving the piezoelectric radiator. Besides, it is extremely difficult to change the focus position in the direction perpendicular to the wave propagation.

The most promising method of focusing, in all probability, is the application of radiators consisting of a set of independent elementary radiators mounted on a flat, spherical or parabolic plate (phased array). In this case, by controlling the electrical characteristics of elementary radiators (changing the phase and amplitude), you can change the position of focus in some volume without changing the geometry of the applicator. Precisely such devices operating in the frequency range from 200 kHz to 10 MHz with acoustic power in the range of 10-30 W/cm2 demonstrate the best results for tumor destruction, which have been reported in monographs [1, 2] and papers [3, 4]. On the other hand, numerical calculations, according to monograph [16] indicate that in order to obtain the shock wave with the required amplitude using small radiators (with an aperture of ~200 mm) the frequency range is equal to 1-3 MHz. For frequencies less than 1 MHz it is difficult to implement the shock-wave mode of radiation at such radiator sizes [29, 30, 31].

The matrix structure of the applicator leads to the need to get answers to several questions. These are the shape and size of the elementary radiator, and the density of the radiator surface filling with elementary radiating elements. Radiators with aperture diameters of 100-300 mm are currently used. To obtain the maximum therapeutic effect, it is necessary to obtain a high concentration of energy in the focal spot which implies the use of high power US close to the existing technological limit (40 W/cm), as is proven in the monograph [17]. Therefore, to reduce the unit power of the elementary radiator and while maintaining a high total power of the signal in focus, it is necessary to break down the surface of the radiator into the maximum possible number of elementary radiators with minimal losses due to technological gaps.

The high density of the applicator surface filling with radiating elements makes it possible to use the radiating surface as efficiently as possible and to compensate for large energy losses during the propagation of ultrasound due to attenuation in living tissues. Application of radiators with the filling factor (ratio of the total area of the array elements to the area of the radiator) less than 65% does not make it possible to realize the shock-wave mode of radiation at the predetermined geometric dimensions. The reason is that the attempt to compensate for losses by increasing the initial signal intensity on the elementary radiators leads to exceeding the existing technological limit (40 W/cm), as demonstrated in publications [17, 18]. According to the results of calculations presented in the paper [16], for successful ultrasonic neurosurgical operations, it is possible to use arrays with the working frequency of 1 MHz, aperture D = 200 mm and filling factor over 80%. At lower values of density, the efficiency of the radiator was sharply reduced.

3. CALCULATION OF ELEMENTARY RADIATORS

The active elements of elementary ultrasonic radiators are piezoelectric elements. This component is a part made of piezoceramic material with electrodes placed on certain surfaces. Now, there is a wide range of piezoceramic materials designed for the use in various applications, referred to in monographs [18, 19, 20]. The practicability of application of one or another material for manufacturing of elementary ultrasonic radiators is determined first by the following characteristics. High values of the piezoelectric module d33, electromechanical coupling coefficient K and quality factor Qm provide high specific power rating, high efficiency and electroacoustic efficiency of the transducer. The low dielectric loss coefficient tan(δ) provides a more economical operation mode of the device due to the reduction of heat losses in piezoceramic material. Table 1 presents characteristics of the piezoceramic materials most suitable for the manufacturing of ultrasonic radiators.

Table 1: Main properties of piezoceramic materials for ultrasonic transducers presented in papers [21, 23]

Name of material	d33, pC/N	C, m/s	K	tan(δ)	Qm
PZT-50 (Russia)	470	3000	0.73	0.025	80
PZT-19 (Russia)	300	2950	0.60	0.028	80
VA-460 (Russia)	315	3200	0.70	0.003	1200
PZT-4 (the USA)	389	2900	0.58	0.004	500
PZT-5A (the USA)	374	2950	0.60	0.02	75
PZT-8 (the USA)	218	3200	0.50	0.004	1000
KNN	420	3400	0.50	0.02	500

Materials based on lead zirconate titanate (PZT) and lead-free materials of the family of sodium-potassium niobates doped with Sb, Bi, Zr ions (KNN) listed in the paper [21] are presented here. However, despite the relatively high figures, KNN family materials are currently not industrially produced and are not available on the market. American materials PZT-4 and PZT-8 and their Russian analogues VA-460 and PZT-50 to the fullest extent meet the requirements for ultrasonic transducers with the acoustic power of 10-30 W/cm2.

Focused radiators based on a single spherical piezoelectric element are simple, but require mechanical movement of the instrument to change the focus position. Multielement radiators do not have this disadvantage and allow the focus position to be changed without moving the radiator. The piezoelectric elements can be placed both on the sphere surface and on the plane surface. The issue of arrangement of the piezoelectric elements is still to be relevant. The arrangement has to ensure that the focus position can be changed without significantly reducing the amplitude in the focus and without the formation of secondary focuses. In this case, the radiator must provide the necessary power with a limited size of the radiating surface. Phased arrays are distinguished both by the number of elements and by the character of their arrangement. Figure 1 presents random (a) and determined (b) variants of elements' arrangement.

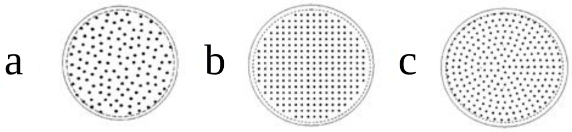

Figure 1: Arrangement of piezoelectric elements in different arrays: (a) – in a random order, (b, c) – arrays ordered in different ways.

Calculations presented in the paper [22] have shown that in the case of the array, which consists of randomly arranged 256 elements (a), there is a possibility to move the focus in the volume 80×30×30 mm. In the case of reduction in the number of elements to 128, the possibility of moving the focal spot is limited to the volume of 40×10×10 mm. For the array consisting of 256 order elements, there is no possibility to move the focus.

In the case of the determined array aperture and technical restrictions on the radiation intensity value of the unit area of its elements, almost the only possibility to increase the intensity in focus becomes the maximum dense arrangement of elements on the array surface. Therefore, an alternative to the abovementioned radiators can be an array with a spiral arrangement of elements (Fig. 2) described in the paper [23]. In this case, the centers of identical square elements are located on the Archimedian spiral. In this configuration, it is possible to achieve the densest packing of elements, which leads to an increase in intensity in focus, proportional to the square of the area of all its elements.

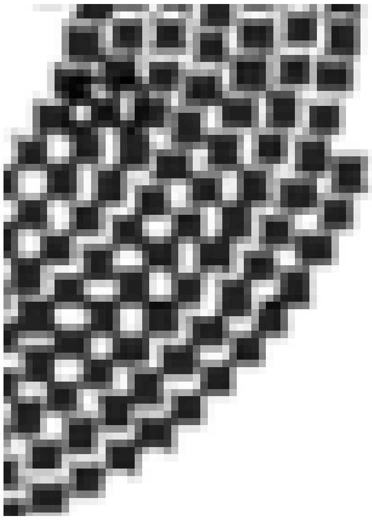

Figure 2: Fragment of phased array with a spiral arrangement of square elements

Authors of the articles [24, 25] propose arrays in the construction of which the method of computer graphics is used with an equally dense filling with various elements of arbitrary areas, according to paper [26].

Based on this method in the paper [24], an algorithm that allows you to break down an arbitrary area into a predetermined number of subareas of the equal area has been proposed. In such a way, the array surface in the form of the sphere segment is divided into the required number of radiating elements (256, 512, or 1024) by using a modified mosaic with cells of the specified area arranged in a random way. For example, for the array with an aperture of 200 mm containing 256 elements the maximum dense filling is achieved with the area of elements equal to 121 mm2.

The equality of areas ensures a high quality of the array field, and their random arrangement makes it possible to significantly reduce the manifestation of side diffraction effects associated with the periodicity of the elements' arrangement.

However, the manufacture of such elements is connected with some technological difficulties because of the great variety of their particular dimensions and shapes (see Fig. 3). To overcome this difficulty, it is possible to place in each such polygonal cell a square or circular element with an area approximately 10% smaller than the cell area (see Fig. 3b). In this case, the distribution remains stochastic, and the filling density remains above 80%. At the same time, the manufacturing procedure for elementary radiators is greatly simplified. On the other hand, the rapid development of 3D printing technology of piezoelectric ceramic materials, according to papers [27, 28] gives hope that soon there will be a possibility to produce piezoelectric elements of any configuration. In this case, all elements of the array illustrated in Fig. 3a can be printed simultaneously.

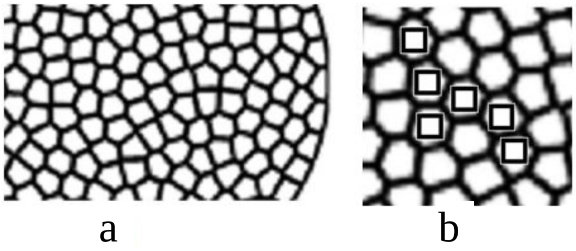

Figure 3: (a) – a fragment of the phased array, whose elements have the form of spherical polygons, (b) – a variant of filling cells with squares of different areas

Considerations have been provided above, according to which it is possible to determine the shape and dimensions (across the direction of sound propagation) of the elementary radiator. A simple ratio from the paper [19] can be used to determine the remaining geometric size h (thickness) of the radiator along the direction of sound propagation:

$$fo = \frac{c}{2h}$$

where f0 is the radiator's eigenfrequency by the thickness, c is the speed of sound in the material.

In this case, it is assumed that the radiator will operate at frequencies near the eigenfrequency f0. For example, if the operating frequency of the elementary radiator is 1MHz, and the sound speed is ~3000 m/s (see Table 1), then the thickness should be approximately 1.8-2 mm. It should be noted that the piezoelectric multilayer element should have the same thickness.

4. CONCLUSIONS

The SWT machine must have an applicator (ultrasonic radiator), which represents a phased array consisting of several hundred elementary piezoelectric radiators mounted on a metal plate of spherical or parabolic shape. The elementary radiators should occupy at least 80% of the applicator surface. For example, for an array with 256 radiators and an aperture of 200 mm, operating at a frequency of 1MHz, the elementary radiator has the form of a cylinder with the height of 1.8-2.0 mm and a diameter of ~ 11 mm or a rectangular plate of the same height with sides equal to ~ 10 mm. For the manufacture of radiators, it is reasonable to use piezoceramic material PZT-4, PZT-8 (USA) or VA-460, PZT-50 (Russia).

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