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ULTRASONIC PHASED ARRAYS FOR LOCAL HEATING AND DESTRUCTION OF BIOLOGICAL TISSUES

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A design and results of an experimental evaluation of a 70-element linear phased array (operating frequency 1 MHz) intended for endocavitary (transrectal) surgical treatment of chronic prostatic disease are presented. The opportunity of scanning of the focal region in the range corresponding to the maximal prostate dimensions is shown. The acoustic power of the array is 200 W. Computer modeling and comparative analysis of acoustic fields created by two-dimensional phased arrays, intended for ultrasonic surgery or high-temperature hyperthermia of tissues are carried out. The cases of scanning of a single focus and multiple foci are considered. Calculations are fulfilled for arrays with elements distributed on the array surface in a regular manner (square, annular, and hexagonal patterns) or randomly. Criteria for evaluating the quality of the intensity distributions in the acoustical fields created by the arrays are proposed. It is shown, that randomization in the distribution of elements improved significantly the quality of the intensity distributions, suppressing the level of secondary maxima of the intensity in the field, or allowed to reduce in several times the number of elements in the array with the same quality of the intensity distribution.

Ability of ultrasonic focusing systems to evoke local heating and destruction of deep seated biological tissues has been already used in clinical practice, both for hyperthermia of tumors, and for minimally invasive surgery (tissue ablation). The most perspective systems for this purpose are ultrasonic phased arrays providing electronic scanning a focus or multiple foci within a given volume of tissues and to achieve the temperatures, required for high-temperature hyperthermia of tumors and destruction of tissues [1-3].

There are two modifications of the phased arrays intended for ultrasonic surgery and therapy: two-dimensional arrays installed outside the body of a patient, and linear arrays installed inside the body. We have developed a linear phased array intended for endocavitary (transrectal) surgical treatment of chronic prostatic disease [4]. The array consists of 70 elements of width 1 mm and length 15 mm (operating frequency is 1 MHz). The schematic sketch of the array and block diagram of a system for driving the elements are shown in Fig. 1. The array was located in the housing which greatest size in the widest part did not exceed 26 mm, and the smallest one in the narrowest part was 15 mm. The housing was enclosed in a rubber membrane, the distance between the array surface and the membrane being about 10 mm. The acoustic contact between the array and biological tissue was provided by means of cold (for cooling the array) degassed water fed into the space between the housing and the membrane. The acoustic power of the array was 200 W that more than enough for thermal destruction of tissues. Experimental investigations carried out have shown an opportunity of steering the focus in the range, at least, 30-60 mm along the acoustic axis and ± 20 mm in the perpendicular direction (which corresponds to the maximal prostate dimensions) with practically acceptable levels of secondary maxima of the intensity outside the focal region [4].

Potential opportunities of the application of externally applied two-dimensional phased arrays are much wider (alongside with surgery of prostate this is the treatment of tumors of liver, kidney, breast, bladder, etc.). Such the arrays are of a special interest because they allow to create multiple foci simultaneously in a given volume and by that to reduce essentially the duration of medical procedure [1, 3, 5].

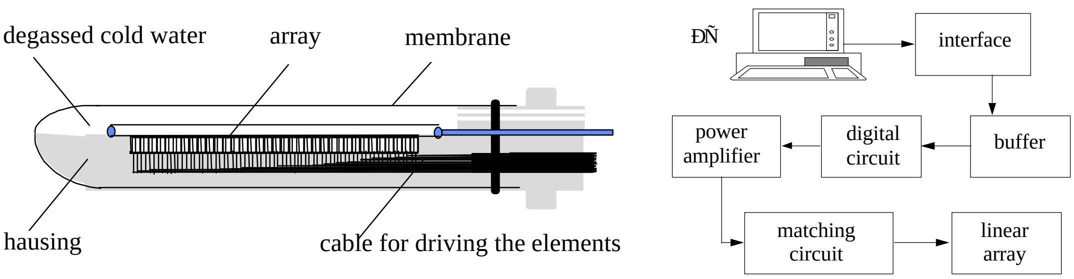

Fig. 1. Schematic sketch of a linear array for surgery of prostate disease and block diagram of a system for driving the array elements.

We developed a method of computer modeling of the acoustic fields created by two-dimensional phased arrays for cases of creation and scanning of both single focus or simultaneous multiple foci [5-7]. The calculations were carried out for the arrays with elements distributed on the array surface in the regular manner (square, annular, and hexagonal patterns) and randomly. The purpose of modeling was to reveal the designs of the arrays that, in spite of the rather small number of elements, provide an opportunity to minimize the influence of secondary maxima of the intensity and, hence, to increase the safety of possible applications of such systems in surgery.

First of all, the case of scanning of the single focus by the array, which surface represented a part of a sphere with the diameter of 110 mm and with the radius of curvature of 120 mm, was considered. The influence on performance of the number of circular elements (varied from 64 to 1024), their diameter (2.5 to 10 mm), frequency (1 to 2 MHz), and also the level of sparseness of elements on the surface of the array was investigated. Four criteria were selected to assess the “quality” of the normalized intensity distributions calculated for the above arrays used in the single focus mode. First, an intensity distribution was deemed to be ‘grade A’ when intensity $I \geq 0.1\ I_{max}$ occurred only within the focal region and was absent in the remainder of the plane investigated. The intensity distribution was described as ‘grade B’ when there were less than 10 localized areas in which the intensity was in the range $0.1 \leq I - \leq 0.15\ I_{max}$ outside the focal area in the plane considered. Intensity distributions with more than 10 localized areas outside the focal area in the plane considered in which $0.1 \leq I < 0.15\ I_{max}$ were classified ‘grade C’. Finally, further discrimination amongst poor intensity distributions was provided by a ‘grade D’ classification for those where there was at least one localized area in which $I \geq 0.2\ I_{max}$.

The results of calculations show that the array consisted of 256 elements, each 5 mm in diameter, randomly distributed on the shelf and driven at the frequency of 1 MHz could steer the focus up to ± 20 mm off the array axis over ranges from 50 mm to 130 mm and still achieve the best quality rating (grade A). At 1.5 MHz, the distances over which the focus could be steered compatible with A and B ratings were ± 10 mm for ranges within 70 mm to 120 mm and ± 14 mm for ranges from 50 mm to 120 mm, respectively. The volume over which a grade A (B) intensity is maintained varies from 63 (106) cm^3 at 1 MHz, through 16 (49) cm^3 at 1.5 MHz , to 12.5 (16) cm^3 at 2 MHz (Figure 5c), respectively.

Fig. 2 illustrates the ability of random and regular arrays to steer the single focus along the axis of the array and in the perpendicular direction. Here, with the use of the criteria mentioned above, the results of the assessment of the intensity distributions created at the frequency of 1.5 MHz by the arrays with a random distribution of elements and with regular distributions (square, annular and hexagonal configurations) are compared. It is seen, that the quality of the intensity distributions of the arrays consisting of 255 or 256 5-mm elements with the regular distributions of the elements (Figs. 2b, 2c and 2d) was much lower than for the randomized array of 256 elements with the diameter of 5 mm (Fig. 2à). The best quality of distributions among the regular arrays was that associated with the annular pattern (Fig. 2d), with a remark, that significant secondary maxima on the axis were obtained for them.

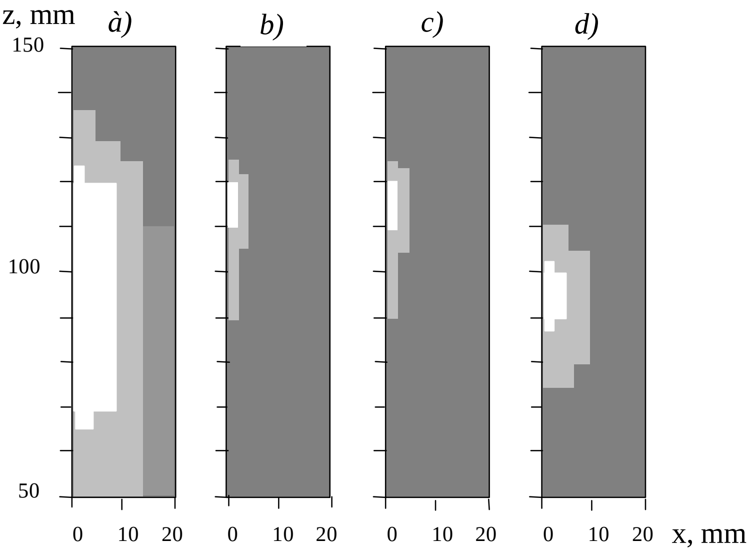

Fig. 2. Assessment of the quality of intensity distributions for the single focus mode associated with arrays consisting of the elements distributed on the shell randomly or in a regular manner. The arrays consist of: a) 256 elements, each 5 mm in diameter, distributed in a random manner; b) 256 elements, each 5 mm in diameter, distributed in a square pattern; c) 255 elements, each 5 mm in diameter, distributed in a hexagonal pattern; d) 255 elements, each 5 mm in diameter, distributed in an annular pattern as 9 concentric rings. The quality levels are: ☐ grade; ▨ B grade; ▩ C grade; ■ grade; z and x - distance along the axis and perpendicular to it.

The performance of the 1024 2.5 mm element square array was considerably inferior to that of the 1.5 MHz 256 5 mm element random array (Fig. 2a) but comparable with the 128 7 mm element random array. This implies that randomization of the elements in the array leads in this case to a (7-8)-fold decrease in the number of elements (and driving channels) that maintains approximately the same quality of intensity distribution. Nevertheless, in all foreign laboratories developing two-dimensional phased arrays for application in surgery, the regular arrays only have been developed. For all of them, the distribution of elements in the square pattern is the most popular from all possible variants.

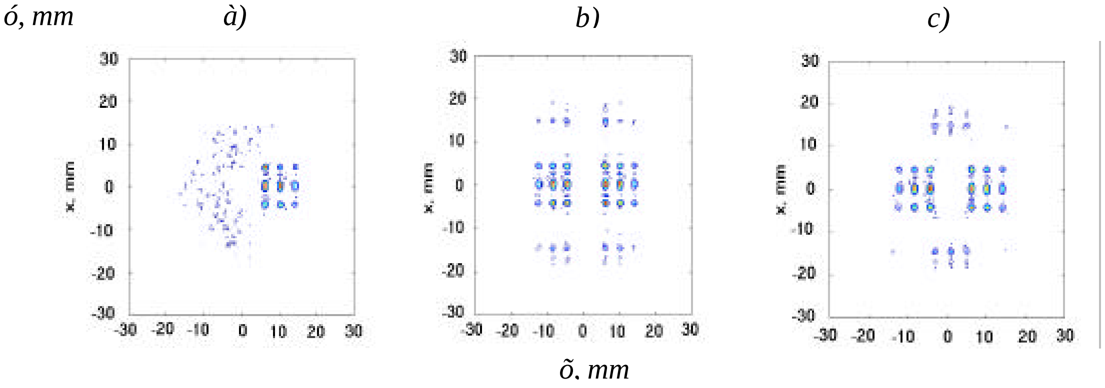

Fig. 3. Intensity distributions in the focal plane at a range z = 100 mm for a 3 x 3 coplanar pattern of foci separated by 4 mm with a central focus steered off the central axis by 10 mm. The distributions correspond to arrays consisting of: a) 256 elements, each 5 mm in diameter, distributed in a random manner; b) 256 elements, each 5 mm in diameter, distributed in a square pattern; c) 255 elements, each 5 mm in diameter, distributed in a hexagonal pattern.

It was of interest to investigate an opportunity of application of the phased arrays for creation and scanning of multiple foci simultaneously [5, 7]. Such opportunity allows to increase essentially the volume of the irradiated tissue and, as a consequence, to reduce the duration of treatment [1]. In Fig. 3, the intensity distributions in the focal plane at the distance z = 100 mm from the surface of the array are presented for steering of 9 co-planar foci located on a 3 x 3 square grid with 4 mm spacing. In the case shown in figure, the central focus was steered off the central axis by 10 mm. The intensity distributions for three variants of arrays consisting of elements, distributed on the array surface randomly or in regular manner (square and hexagonal patterns) are compared. It is seen, that in the case of steering of the multiple foci with the use of both regular arrays (cases b and c) the level of the intensity in grating lobes (secondary maxima of the intensity) approaches to the intensity level in the main lobes, that is unacceptable for practical purposes. Using of random arrays (case à) improves essentially the situation, permitting to suppress the grating lobes.

Thus, the data of modeling show that randomization in the distribution of elements on the surface of two-dimensional phased array results in significant improvement of the quality of the intensity distributions in comparison with the regular distribution of elements (square, annular or hexagonal patterns).

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