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Spiral Arrangement of Elements of Two-Dimensional Ultrasonic Therapeutic Arrays as a Way of Increasing the Intensity at the Focus

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Abstract—The emergence of new ways of applying high-power ultrasound in medicine that are based on using nonlinear fields and shock-wave operation modes requires a substantial increase in the power of phased arrays used for the generation of these fields. The need to develop a new generation of similar arrays based on employing densely packed elements arranged spirally on their surfaces is shown.

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INTRODUCTION

In recent decades, the use of focused, high-intensity ultrasound has become one of the most effective and rapidly developing area of medical physics [1–3]. Ultrasound focusing is most often done using single piezoceramic transducers shaped as part of a spherical shell. Such radiators are relatively simple, inexpensive, and easy to manufacture; these are undoubtedly great advantages. One disadvantage is their fixed focal lengths and thus relatively low flexibility. For the destruction of biological tissue with a relatively large volume (several cm^3 and more), positioners must be used for the mechanical translation of the focusing system. Since it is known from practical experience that this takes several hours, the use of transducers with fixed focal lengths is not always possible in surgery.

Clear preference is given to ultrasonic phased arrays, which allow one to vary the position of the focusing area without mechanical travel of the array itself, and to create several foci simultaneously.

There are two varieties of arrays for ultrasonic surgery and therapy: ones that remain outside the patient's body (so-called extracorporeal arrays) and ones that are introduced into the organism (intracavitary arrays). The former arrays have no restrictions on their spatial dimensions or number of elements.

In recent years, there has been a clear trend toward raising the intensity of ultrasound when treating tissues with focused ultrasound [1–3]. Investigations have reached a level where they often use intensities at the transducer's surface that are close to those maximally admissible in modern technologies (tens of W cm^{-2}). At the same time, there is a great need to increase the power emitted by a radiator not by further raising the intensity at its surface but by using such previously untried methods as varying the geometry of focusing systems.

This work shows the need to develop a new generation of phased arrays based on employing densely packed elements arranged spirally on their surfaces, and presents possible designs for these arrays.

THEORETICAL APROACH

Before considering actual configurations, let us discuss some general features of creating fields of multi-element arrays. Let us assume the linear character of acoustic wave propagation. The source fields can be described with a high degree of accuracy using the Rayleigh integral [4–6]

$$p(\vec{r}) = -i\rho_0 c_0 \frac{k}{2\pi} \int_S \frac{V(\vec{r}')e^{ik|\vec{r}-\vec{r}'|}}{|\vec{r}-\vec{r}'|} dS. \qquad (1)$$

Here, p is the complex amplitude of acoustic pressure at the point with coordinate $\vec{r}$, V is the amplitude of the normal component of the velocity of the emitting surface; $\vec{r}'$ is the radius vector of surface element dS, $k = \omega/c_0$ is the wave number, ω is the angular frequency; and ρ_0 and c_0 are the density and speed of sound of the medium. Let us assume that the source is monochromatic, and the oscillatory velocity and acoustic pressure change over time as $\exp(-i\omega t)$. Integration is peformed along emitting surface S. Formula (1) enables us to calculate the acoustic field in space, based on the distribution of the normal component of the oscillatory velocity at the source's surface. When this surface is a part of a sphere with radius F (as in the case of focusing transducers), the expression for acoustic pressure amplitude P_F at the geometric focus (at the sphere's center, where $|\vec{r} - \vec{r}'| = F$) takes the simple form

$$P_F = -i\rho_0 c_0 \frac{k e^{ikF}}{2\pi F} \int_S V(\vec{r}\,')\, dS. \quad (2)$$

When the source is a multi-element array with constant vibrational velocity $V = V_0$ at the element's surface and zero velocity outside the elements, a simple expression for the amplification factor of the focusing system follows from (2):

$$K_F = \left|\frac{P_F}{P_0}\right| = \frac{S_0}{\lambda F}, \quad (3)$$

where $P_0 = \rho_0 c_0 V_0$ is the characteristic amplitude of the acoustic pressure at the emitting surface, $\lambda = 2\pi/k$ is the wavelength, and S_0 is the total area of all active elements. Any increase in pressure at the focus relative to the characteristic pressure at the element surface is thus independent of the specific nature of the position of elements on the spherical surface of the source and is determined only by area S_0. This means that the determining parameter is the density of array packing by active elements:

$$\Psi = \frac{S_0}{S}. \quad (4)$$

Here, S is the total source area. Expression (3) is equivalent to

$$K_F = \Psi \frac{S}{\lambda F}, \quad (5)$$

i.e., with certain geometric dimensions of the source, the amplification factor for the wave amplitude at the geometric focus is proportional to packing density Ψ. Arrays with close packing of elements where coefficient Ψ is close to 100% are therefore best for obtaining high-intensity fields.

As was mentioned above, apart from attaining high intensity at the geometric focus, one reason for using an array is the possibility of dynamic focusing through the suitable phasing of elements. Here, the scale and nature of element arrangement is of importance; i.e., the problem of optimization is more complex.

HIGH-POWER TWO-DIMENSIONAL ULTRASONIC ARRAYS FOR MEDICINE

Until recently, the two-dimensional phased arrays developed and produced in a number of laboratories were only regular, and the arrays most often used square elements closely packed in the nodes of a square array [7–11]. Our studies indicate this is the least appropriate element arrangement.

The surfaces of such arrays are densely packed with active elements (despite the technological gaps between elements, packing density Ψ can exceed 90%); according to (5), these arrays are effective in obtaining high intensities at the geometric focus. However, such radiators have a substantial disadvantage: secondary intensity maxima in their acoustic fields, due to the discrete structure of the array and the regular arrangement of elements in it. Such maxima can result in overheating and even the destruction of biological tissue outside a given area of action. As is well known, in order to eliminate side lobes in the array directivity diagram, the distance between the elements' centers must be $<\lambda/2$ [11], where λ is the wavelength (e.g., <0.5 mm at a frequency of 1.5 MHz). However, in order to develop an array with sufficiently large aperture and such small element dimensions, and at the same time attain the acoustic powers needed for a therapeutic array, it is necessary to use a considerable number of elements and electronic channels. Reducing the level of side lobes in the array directivity diagram by lowering the amplitude on the array's elements from its center to periphery [11] is also unacceptable because of the high requirements for the acoustic power of the array. Yet another method based on using arrays with unequal distances between element centers [11] was tested in [12], where it was shown that the reduction in the level of secondary intensity maxima can be as great as 30–45%, compared to arrays with equal distances between elements (so-called equidistant arrays). Such approaches as using wide-band signals for the excitation of array elements [13] are also ineffective and are not used in actual array designs.

To enhance the quality of acoustic fields generated by high-power two-dimensional arrays, a number of researchers have proposed an approach based on the use of sparse arrays with randomly arranged elements [5, 14–16]. The logic of this approach is that the level of side lobes in the field generated by an array largely depends on the regularity of the array's structure. This means that a random arrangement of elements on a two-dimensional array's surface could improve the quality of ultrasonic intensity distributions as estimated from the presence of secondary intensity maxima in the field generated by the array, compared to regular arrays.

At the same time, it was shown in [14] that randomization of an array's element arrangement alone is not enough to ensure the high quality of acoustic fields with the steering of a focus (or several foci). To attain such quality, the radiation of each element must be not too directed; i.e., element dimensions must be no greater than several wavelengths (at most, 5λ). Finally, array sparseness must not be too high: lowering the packing density to <35–40% notably increases the power generated by the array and lowers the quality of the field distribution. Together, these three factors are the main distinguishing features of our technical solutions [17]. It is important to note that to attain high quality of the fields generated by the array, these three conditions must be satisfied simultaneously, and ignoring any of them increases the number of secondary intensity maxima.

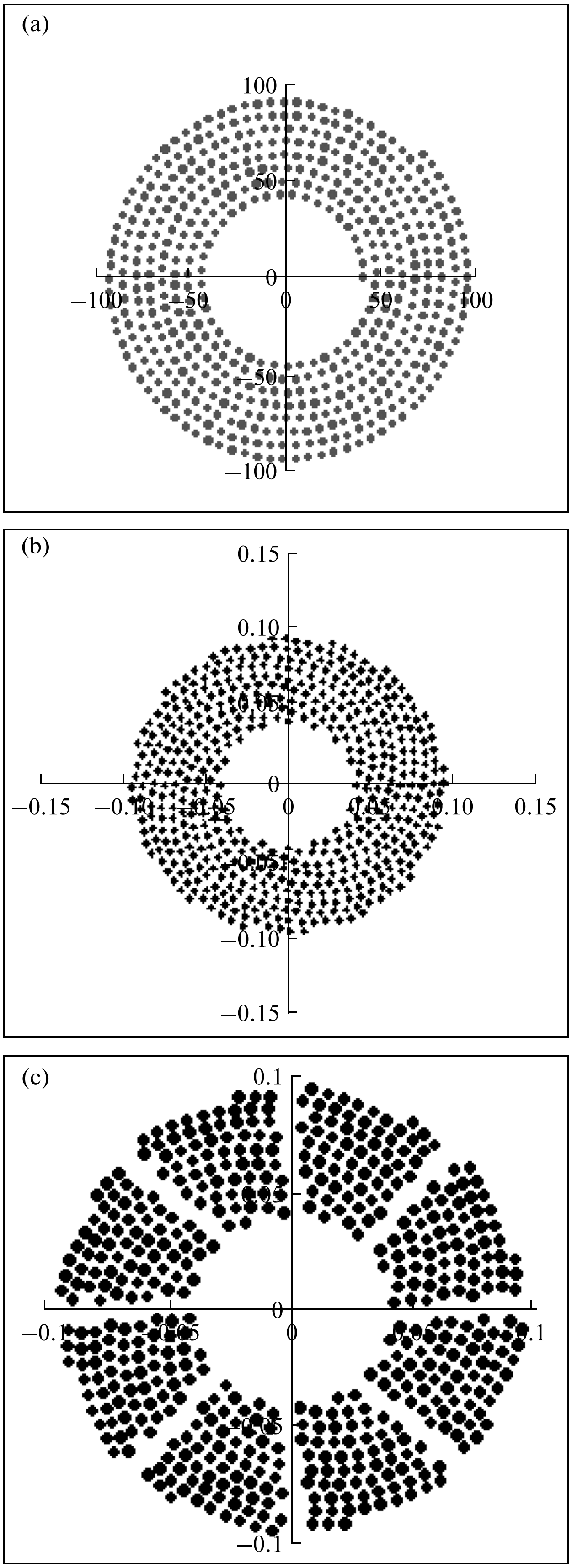

Fig. 1. Configuration of investigated spiral arrangements of elements on a randomized array's surface.

Several foreign laboratories have now developed and used randomized phased arrays for surgery that follow these principles [18–20]. Prototypes of similar devices have been made and used in studies in tissues ex vivo, and the possibility of their clinical application was demonstrated.

At the same time, the question arises of whether or not side lobes can also be avoided in dense packing of elements. In this connection, recent studies in which elements were arranged on an array's surface in spiral patterns are worthy of note (Fig. 1). This simple and effective solution that we proposed and studied in 2010 [3] allows one to arrange elements as densely as possible on an array's surface and simultaneously eliminate periodicity in their arrangement. Multiple calculations of the fields of arrays with spiral arrangements of elements show the advantages of this approach. This concept was used by other researchers in [21, 22].

RESULTS AND DISCUSSION

The effect of dense packing on the maximum intensity at the focus was considered, and the quality of intensity distributions in a randomized array and an array with dense spiral packing of elements at the surface was compared.

The fields of two arrays with 512 elements with an operating ultrasound frequency of 1 MHz were compared. They differed in that the first was composed of elements in a disk shape with a diameter of 6 mm, arranged randomly on the array's surface (Fig. 2a); the second contained square elements with sizes of 6 × 6 mm, the centers of which were arranged on the Archimedean spiral (Fig. 2b). Both arrays had a central hole for the diagnostic probe.

The parameters of the first array were: diameter, 200.6 mm; radius of curvature, 150 mm; central hole diameter, 75 mm; intensity at an element's surface, 5 Wcm^{-2}; maximum and minimum distances between element edges, 0.44 and 1.35 mm, respectively.

Elaments in the second array were arranged on a spiral (Fig. 2b). The minimum gap between them was 0.5 mm; the way in which they were arranged is shown in Fig. 2c. The distance between the adjacent spiral turns was constant with the presence of the comparatively large central hole and equal to the sum of the element diameter and a specified technological gap of 0.5 mm. Other parameters of the second array were: array diameter, 191.3 mm; radius of curvature, 150 mm; central hole diameter, 75 mm; intensity at an element's surface, 5 W cm^{-2}.

Note that to enlarge packing density, the element shape can be made trapezoidal.

The quality of intensity distributions in acoustic fields was calculated and estimated using methods based on Rayleigh integral (1) [14]; our results are presented in the graphs shown below (Fig. 3).

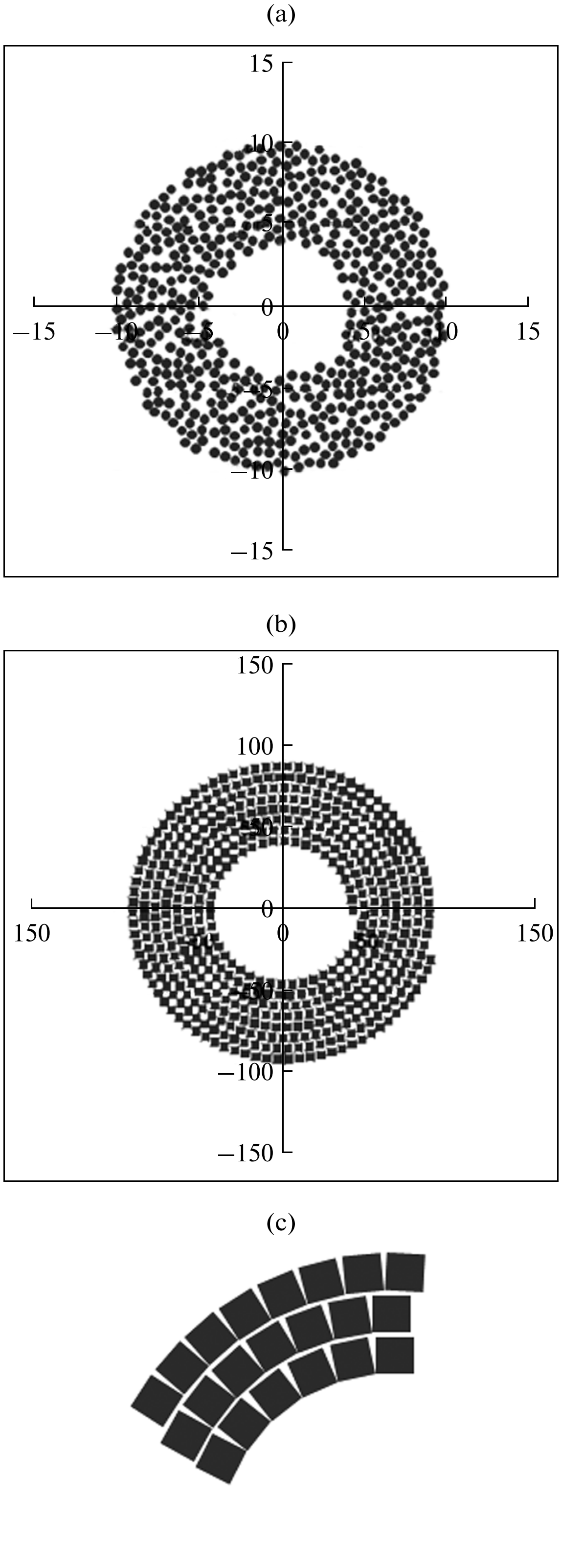

Fig. 2. Two randomized arrays (frequency, 1 MHz) composed of 512 elements: (a) array of elements in the shape of disks 6 mm in diameter, randomly arranged on the array's surface; (b) array of square elements (6 × 6 mm) with centers located on an Archimedean spiral; (c) way of arranging elements in spiral array (b).

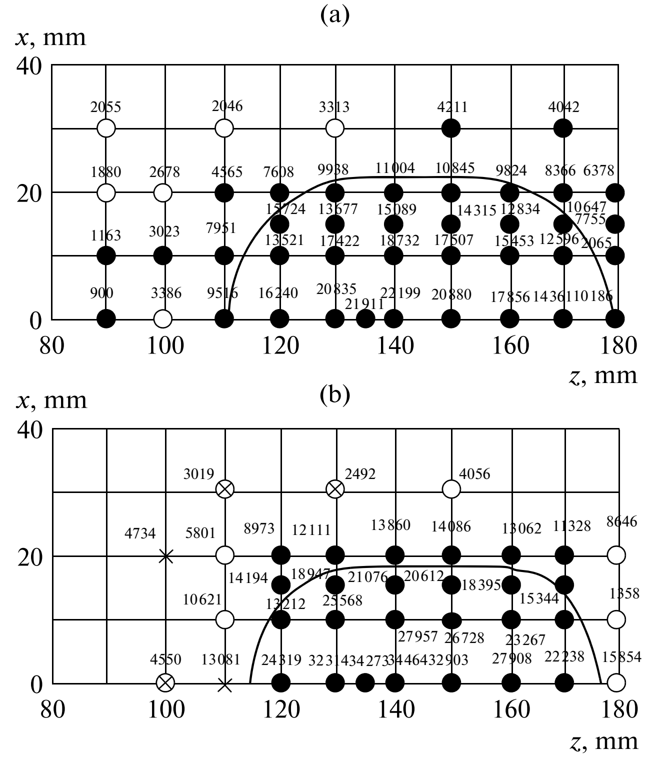

Fig. 3. Data from calculations of the intensities at the focus and the quality of acoustic fields of two randomized arrays with different degrees of element packing in the scanning mode of a single focus: (a) array with disk-shaped elements 6 mm in diameter, arranged quasi-randomly; (b) array with square elements (6 × 6 mm) arranged in the shape of an Archimedean spiral. Quality estimates are according to [14]: (●) grade *A*; (○) grade *B*; (×) grade *C*; (⊗) grade *D*.

Black dots correspond to grade *A* quality, i.e., the absence of secondary intensity maxima in an array field with an intensity of $\geq 0.1 I_{max}$, where I_{max} is the maximum intensity at the focus. Figures near the signs correspond to intensity W cm^{-2} at the focus when it was moved to a given point. The curve within the graphs corresponds to the area limited by an intensity of $0.5 I_{max}$. Practical use of arrays with higher intensities at the focus is not advisable if the focus is moved outside this area.

It is evident that for both cases, the maximum intensity at the focus corresponds not to the geometric center of the array curvature, but to a point (0, 0, 140 mm) which is 10 mm closer to the array than the geometric focus. With the randomized phased array (Fig. 3a), the maximum intensity at the focus is 22 199 W cm^{-2}; for the second densely packed array, it is 34 864 W cm^{-2} (greater by a factor of 1.57). This result might be expected, since the active area of the densely packed array was approximately 25% greater, and the intensity rose by a factor of $(1.25)^2$.

Note that the size of the area that corresponds to the effective use of the array and is bounded by the curve in Fig. 3 becomes notably smaller for the densely packed array (by approximately 4–5 mm in the range of $z = 130–160$ mm). The volume of such an effective array shrinks from approximately 80 to 50 cm^3. This very substantial reduction is due to the attaining of high intensity in the main intensity maximum. The reason for this effect is that the effective dimension of a square element is greater than for an element with the disk shape, and the square element directivity diagram becomes narrower than the one for the latter. This inevitably reduces the effective scanning area. The scanning zone in the spiral array can be widened by substituting round elements for square ones; at the same time, however, the packing density and the associated maximum intensity at the focus, which is determined by the total area of the active elements of the array, fall simultaneously. Still, the manufacture of therapeutic two-dimensional arrays with elements in the disk shape and with centers located on the spiral can be useful in designing compact arrays.

It should be noted that the very compactness of two-dimensional therapeutic arrays allows one to obtain the required characteristics of ultrasonic fields using relatively small focusing systems.

What is the most promising field for the use of densely packed arrays, and why is it necessary to investigate and develop them? Such arrays will find practical application when for some reasons it is necessary to attain the greatest possible intensities at the focus. In recent years, the possibility of increasing the maximum intensity at the focus of densely packed arrays has been of special interest in medical acoustics due to the rapid development of the new scientific field of using nonlinear effects in superpower and strongly focused ultrasonic beams [23, 24]. The state-of-the-art devices employed in ultrasonic surgery have an intensity of 25 kW cm^{-2} in the focal region, resulting in the generation of higher harmonics in the spectrum of a propagating wave, asymmetric distortion of the wave profile, the formation of acoustic pressure discontinuities (shock fronts), and additional dissipation of the wave energy on the aforementioned discontinuities. The pressure jump at the shock can be as high as 60–80 MPa. Local ultra-fast (in several milliseconds) heating of tissue to temperatures above 100°C and boiling are then possible. The efficiency of absorption at discontinuities can exceed the linear absorption in the tissue more than ten times. At the same time, the time of boiling in the tissue can be determined from simple analytical estimates based on the theory of weak shock waves. The effects of ultra-fast heating to boiling temperatures in a tissue as a result of shock formation are extremely important when using focused ultrasound at super-high intensities, since the formation of vapor bubbles during boiling in tissue cardinally alters the action of the ultrasound on it [25–29].

CONCLUSIONS

(i) Our investigation of two array configurations (an array of disk-shaped elements randomly arranged on an aperture with somewhat greater diameter and an array of square elements with centers on an Archimedean spiral) shows that using the array of spiral configuration allows one to obtain a substantial gain in the maximum intensity at the focus. At the same time, the size of the scanning area of such arrays is somewhat smaller than for arrays with random arrangements of round elements.

(ii) The scanning area of spiral arrays can be widened by substituting disk-shaped elements for square ones.

(iii) The choice of one type of array or another depends on the main objective, e.g., to attaining maximum intensity at the focus or have a focus steering area with the greatest possible volume and acceptable intensity.

(iv) The spiral arrangement of elements with a given array aperture is better than other configurations (randomized or periodical), since it allows a denser packing of elements and produces maximum intensity at the focus without an increase in the secondary maxima in the array field.

The current trend toward an increase in ultrasound intensity at the foci of focusing systems under the action of short-term pulses on tissues will inevitably result in new and better examples of using superpower two-dimensional arrays with the dense packing of elements.

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