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Mathematical modeling of method to control parameters and location of focal spot in ultrasonic surgery

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A study of methods for correcting the location of a focal spot formed by antenna arrays in the form of a spherical segment with different opening angles in a layered-heterogeneous biological environment was made. The use of the mean-thickness sound velocity in biological tissues as a calculation for the matching layer makes it possible to obtain satisfactory results for correcting the location of the focal spot formed by antenna arrays with the opening theta angle of the spherical segment equal to 60, 90 and 120^{circ}. An algorithm for correcting the location of the focal spot based on changes in the physical characteristics of the matching layer is proposed.

Keywords: layer thickness averaged speed of sound, focused ultrasound, focal spot, matching layer, control method.

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The environment for propagation of powerful focused ultrasound used for surgical purposes has a layered-heterogeneous structure represented by a matching fluid layer, skin, fat and muscular tissues. Table 1 shows data from literature sources [1,2] on the acoustic characteristics of the listed layers. The formation of a focused ultrasonic field in a layered-heterogeneous biological environment changes the geometry and location of the focal spot, as well as the amplitude of the acoustic pressure at the focus. This affects the effectiveness and safety of the using the powerful focused ultrasound in medical surgery. The actual task is to develop a method for precise aiming of ultrasonic focus, adjustment of its location and parameters of focal spot while passing through the layered biological structure taking into account peculiarities of the patient's body structure. The purpose of work is to evaluate the effectiveness of a method for adjusting the focal spot location based on changing the physical characteristics of the matching layer, calculated from the layer thickness averaged speed of sound in biological tissues, for antenna arrays with spherical segment opening angles $\theta = 60$, 90 and 120°.

The works [3,4] have investigated a method of controlling the focal spot formation based on changing the physical parameters of a matching fluid layer enclosed in a bellows. A solution of glycerin in distilled water is proposed to change the sound speed in the matching layer in [3,4]. The density and attenuation coefficient of ultrasonic waves are determined from the calculated solution concentration. The work [4] proposes a method for calculating the required parameters of the matching layer based on the calculation of the layer thickness averaged speed of sound c_{avt} in biological tissues. This requires knowing the thicknesses and sound speeds in each layer in the ultrasonic wave propagation path:

$$c_{avt} = (h_2c_2 + h_3c_3 + h_4c_4)/(h_2 + h_3 + h_4),$$

where c_n is the sound speed in the layer, h_n is the layer thickness, n is the layer order number (1 — the matching fluid layer, 2 — the skin tissue, 3 — the fat tissue, 4 — the muscular tissue).

The following simplifications were used to derive the formula to determine the layer thickness averaged speed of sound in [4]: the biological tissue layers were assumed to be flat and parallel, and the slope angle of the acoustic rays relative to the interface was not greater than 30°. However, antenna arrays used for medical surgery are not limited to small transmitter slope angle [5,6]. Changes in the geometry and position of the focal spot depend not only on the structure of the layered-heterogeneous biological environment, but also on the opening angle of the spherical segment of the antenna array θ. Therefore, it is necessary to evaluate the effectiveness of this method to calculate the matching layer parameters to control the focal spot location generated by antenna arrays with $\theta > 60^{\circ}$ angle.

Using the model described in [3], the focused ultrasonic field passage through layered biological media has been mathematically simulated. Biologic layer combinations (BLC) characteristic of different patient sizes as well as localization of the neoplasm in the subcutaneous tissues were chosen for comparison. Table 2 shows the layer thickness ratios and design parameters of the matching layer required to adjust the focal spot location. For calculations, the biological tissue layers are assumed to be flat and parallel. Table 2 et seq. uses a conventional alphanumeric designation for combinations of biological layers: BLC 1 – normal build, BLC 2 — athletic build, BLC 3 — heavy build, BLC 4 – subcutaneous neoplasm. The designation

Table 1. Acoustic characteristics of the ultrasound propagation environment (as per [1,2])

Propagation environment	Sound speed c, m/s	Environment density ρ, kg/m^3	Attenuation coefficient α, m^{-1} (at $f = 2$ MHz)
Distilled water (at 22°C)	1489	1000	0.12
Glycerin (at 20°C)	1923	1261	2.33
Skin tissue	1610	1250	80
Fat tissue	1450	930	26
Muscle tissue	1570	1070	40

Table 2. Layer thickness combinations and calculated parameters of the matching layer to ensure the adjustment of the focal spot location

Designation of layered system	Ratio of layer thicknesses, mm	Matching layer parameters			
		Sound speed c_{avt}, m/s	Concentration of glycerin solution in water k_v^*, %	Density ρ^*, kg/m^3	Attenuation coefficient α^*, m^{-1} (at $f = 2$ MHz)
BLC 1	138−2−30−30	1513	5.7	1015	0.25
BLC 2	138−2−10−50	1552	14.6	1038	0.44
BLC 3	108−2−60−30	1493	0.9	1002	0.14
BLC 4	188−2−5−5	1527	8.8	1023	0.31

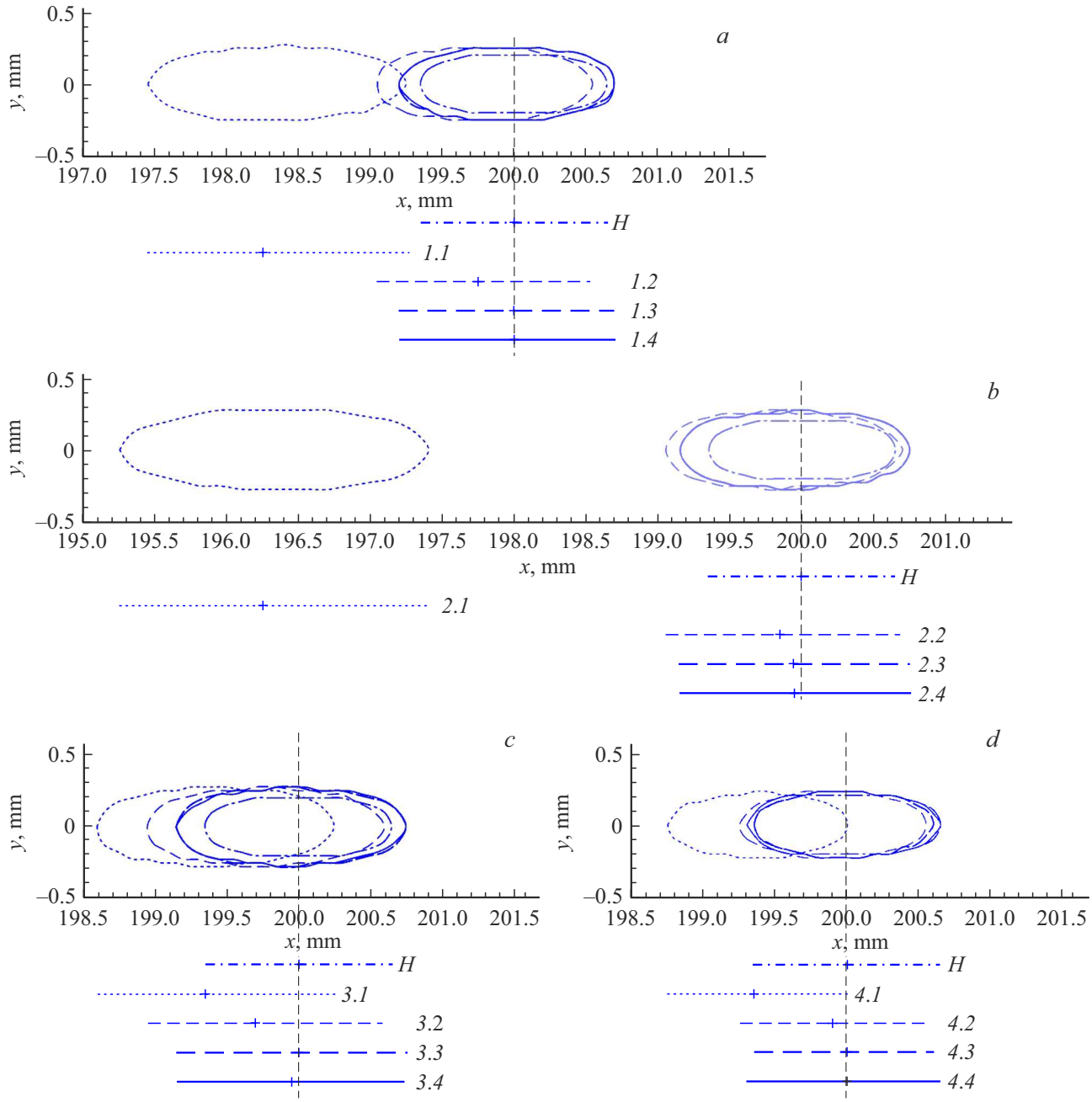
Table 3. Deviation Δx of focus „point“ from the geometric focus of the antenna array and the longitudinal dimensions of the focal spot Δl

Propagation environment (adjustment method)	Spherical segment opening angle of the antenna array					
	$\theta = 60°$		$\theta = 90°$		$\theta = 120°$	
	Δx, mm	Δl, mm	Δx, mm	Δl, mm	Δx, mm	Δl, mm
Homogeneous environment	−0.05	4.7	0	2.2	0	1.3
BLC 1*	−1.55	4.45	−1.5	2.15	−1.75	1.8
BLC 1 (TAV)	−0.45	4.55	−0.2	2.2	−0.25	1.5
BLC 1 (PHA)	−0.35	4.45	−0.05	2.25	0	1.5
BLC 1 (COMB)	−0.4	4.55	−0.05	2.25	0	1.5
BLC 2*	−3.25	4.45	−3.6	2.25	−3.75	2.15
BLC 2 (TAV)	−0.45	4.8	−0.15	2.35	−0.15	1.65
BLC 2 (PHA)	−0.35	4.55	−0.15	2.3	−0.05	1.6
BLC 2 (COMB)	−0.4	4.8	−0.15	2.35	−0.05	1.6
BLC 3*	−0.65	4.4	−0.55	2.2	−0.65	1.65
BLC 3 (TAV)	−0.4	4.45	−0.2	2.25	−0.3	1.65
BLC 3 (PHA)	−0.3	4.45	−0.05	2.25	0	1.6
BLC 3 (COMB)	−0.35	4.45	−0.05	2.25	−0.05	1.6
BLC 4*	−0.7	4.35	−0.5	2.1	−0.65	1.25
BLC 4 (TAV)	−0.4	4.65	−0.1	2.2	−0.1	1.3
BLC 4 (PHA)	−0.3	4.4	−0.1	2.1	0	1.25
BLC 4 (COMB)	−0.35	4.65	−0.05	2.2	0	1.35

* The data have been obtained without adjustment.

of layer thickness ratio in Table 2 is represented by the sequence of numbers (in mm): the matching layer from the center of the antenna array, skin tissue, fat tissue, muscular tissue.

Three kinds of antenna arrays with surface radius of 200 mm with spherical segment opening angle $\theta = 60$, 90 and 120° (maximum ultrasonic emitter slope angle 30, 45 and 60°, respectively) have been investigated. The disc-shaped emitters transmitters, randomly positioned on the surface of the antenna arrays, had a diameter of 8 mm. An equal percentage of active surface area was ensured for the antenna arrays. Thus, as the spherical segment opening angle θ of the antenna array increased, the transmitters increased to 321, 703 and 1200 pieces, respectively. The acoustic field was studied in two mutually perpendicular directions: along x axis — along the ultrasonic wave



Changes in the shape and location of the focal spot made by an $\theta = 120^\circ$ antenna array when different adjustment methods are applied. The focal spot contours and their projections onto the axis x for each combination of biological layers and adjustment methods are numerically labelled. The first number corresponds to the sequence number of the biological layer combination: *1* — BLC 1, *2* — BLC 2, *3* — BLC 3, *4* — BLC 4; second number — the way to adjust the focal spot location: *1* — without adjustment, *2* — TAV, *3* — PHA, *4* — COMB. Letter *H* denotes the focal spot and its projection onto the axis x for a homogeneous environment.

propagation direction, along y axis — through the maximum of the acoustic pressure amplitude distribution (at „point" of focus). The study step along the axis x was 0.05 mm, and along the axis y — 0.025 mm. The following parameters were used for the calculations: emission frequency $f = 2$ MHz, study time step 10^{-8} s, signal duration 10^{-3} s.

The acoustic field was calculated for the case of ultrasonic wave propagation in a homogeneous environment — distilled water, as well as for the case of propagation through the combination of biological layers shown in Table 2. The following ways of adjusting the focal spot location were chosen for comparison: by using a matching layer with acoustic characteristics calculated from the layer thickness averaged speed of sound (TAV), by introducing a phase distribution over the antenna array elements (PHA), and by combining the two methods mentioned above

(COMB) [3,7]. The following acoustic field characteristics were used to compare the adjustment methods investigated: 1) deviation of focus „point" from the geometric focus of the antenna array; 2) longitudinal and transverse dimensions of the focal spot (at 0.707 of maximum acoustic pressure amplitude); 3) acoustic pressure amplitude at focus „point".

Table 3 shows the deviation Δx of focus „point" from the geometric focus of the antenna array along the ultrasonic wave propagation direction and the longitudinal dimensions of the focal spot Δl. As the spherical segment opening angle θ of the antenna array increases, the longitudinal size of the focal spot Δl decreases.

The figure shows the focal spot contours at 0.707 of the acoustic pressure amplitude at focus „point" generated by an antenna array with opening angle $\theta = 120^\circ$. For clarity, each contour has its projection onto the axis x and the maximum acoustic pressure amplitude is marked below each contour. From the figure, it can be seen that in the absence of focal spot location adjustment, its displacement Δx appears to be commensurate with its longitudinal size Δl.

Transverse dimensions of focal spot Δh for ultrasonic field propagation in layered-heterogeneous biological media with and without focal spot location correction are $0.75-0.8$ mm at $\theta = 60^\circ$, $0.55-0.6$ mm at $\theta = 90^\circ$ and $0.45-0.55$ mm at $\theta = 120^\circ$. Applying different methods to adjust the focal spot location slightly affects the change in transverse focal spot size Δh (up to 0.025 mm).

For antenna arrays with $\theta = 60^\circ$, applying a focal spot location adjustment method based on changing the physical characteristics of the matching layer (TAV and COMB), compared to the phase method (PHA), gives an additional attenuation of the acoustic pressure amplitude at the focus of up to 5.3%. When the spherical segment opening angle θ increases to 120°, this difference in acoustic pressure amplitude at the focus decreases.

Mathematical modeling has shown that applying different methods to adjust the focal spot location gives results with little difference in displacement of focus „point" focal spot geometry and acoustic pressure amplitude in focus.

The investigated method to calculate the matching layer parameters, based on the computation of the layer thickness averaged speed of sound in biological tissues, provides satisfactory results for adjusting the focal spot location. This calculation method is applicable to antenna arrays with spherical segment opening angles $\theta = 60$, 90 and 120°. The following algorithm is proposed for the practical use of this method of focal spot location adjustment.

1. Positioning of the antenna array at an angle 90° to the target to determine the structure of bio-tissue layers by echolocation.

2. Estimation of the propagation time of ultrasonic waves through each biological layer to the exposure area.

3. Calculation of the biological layers thickness from known values of speed and time of sound propagation in them.

4. Calculation of the layer thickness averaged speed of sound in biological tissues up to the exposure area.

5. Calculation of the glycerin solution concentration in distilled water for the matching layer using the resulting value of the layer thickness averaged speed of sound.

The use of the value of the layer thickness averaged speed of sound in biological tissues greatly simplifies the task of finding the matching layer parameters, providing the adjustment of the focal spot location in layered-heterogeneous biological media.

This article does not contain any researches with participation of a human as the object of studies.

Conflict of interest

The authors declare that they have no conflict of interest.

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