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A Numerical Study of Low-to-Moderately Focused Ultrasound Transducers (CNIB).

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Abstract—**This work presents a numerical study of the linear focal shift effect and the length of the axial focus of low-to-moderately focused ultrasound transducers with a concave spherical geometry and a circular boundary. Single element and annular array transducers were studied. The impact of acoustic losses in the external medium was comparatively considered. In this scenario, it is shown that the linear focal shift effect depends on the acoustic losses of the external medium, but the shift decreases more than the half for the arrays regarding the single element radiators, for a given geometrical focal gain in a linear acoustic context. Additionally, a significant reduction of the length of the axial focus is obtained. These general results can be a contribution for a proper planning of several mild-hyperthermia therapeutic applications currently used, where a geometrically focused ultrasound transducer is employed.**

Key words—Focused ultrasound transducer, length of the axial region focus, linear focal shift effect, ultrasound therapy

I. INTRODUCTION

Ultrasound can induce in the biological tissue diverse molecular, cellular and physiological responses [1]. For several decades this form of mechanical energy has been used in physiotherapy for the management of different musculoskeletal disorders [2]. More recently, intense investigation efforts are uncovering a broader spectrum of ultrasound therapy applications with impressive results [3]. In many of the emerging applications, an increment of tissue temperature or hyperthermia is generated to obtain the desired medical outcomes.

Generally, the hyperthermia effect is obtained by focusing the ultrasound field in the region target. Numerous technologies have been implemented to focus ultrasound energy, but currently the focusing effect is frequently achieved by a spherical curvature of the active transducer [4]. Nevertheless, it is well-known that for geometrically focused ultrasound transducers the true spatial pressure peak appears at a depth closer to the aperture than the geometrical focus, for a linear acoustic system. The distance between these two points is called the linear focal shift [5].

An optimal hyperthermia treatment is spatially accurate with precise and homogeneous heating limited to the target region, while ideally not damaging the adjacent tissue [6]. While high temperatures are required to ablate tissues (>55° C), mild-hyperthermia (40–45° C) can be used to change the properties of a drug delivery vehicle and increase local perfusion [6]. Furthermore, mild hyperthermia may provide improved tissue oxygenation, inhibits homologous recombination, improve delivery of chemotherapy and potentiate its cytotoxic effects, as well as augment immune response.

But, despite the many technological advances, currently hyperthermia applicators are often limited in their ability to provide a spatially accurate thermal therapy [7], [8]. To assist in the management of the problem, non-invasively, image-guided systems are implemented to monitoring *in situ* the temperature of the tissue under treatment. The system comprises an ultrasound therapy transducer with a central hole intended to insert a diagnostic device [4]. However, the introduction of the central hole in transducer leads to an increase in the focal shift effect [4]. Even more, the risk of defocusing is present when treating deep organs, such as the kidney, liver and bladder. On the other hand, the study of the acoustic field characteristics generated by focusing sources in linear regimes is a continuously developing field of research, since linear theories are often more than approximation and constituting the fundamentals of every scientific discipline [9], [10].

This study is dedicated to investigate numerically the linear focal shift phenomenon and the length of the axial focus of low-to-moderately focused ultrasound transducers with a concave spherical geometry and a circular boundary, composed of single element and annular array radiators with a central hole, as are used in numerous to-mild-hyperthermia applications. The numerical simulations comparatively considered acoustic losses in the external medium.

II. THEORY

Diverse analytical expression has been developed for the description of the sound field emitted by the ultrasound transducer with a concave spherical geometry with a circular boundary, including a central hold [4].

Yet, for more realistic conditions, e.g. when losses are considered in the acoustic wave propagation medium, in general numerical integrations are needed. The spatial impulse response (SIR) method provides a general technique for calculating the sound field by convolving the velocity of the piston with the spatial impulse responses of the observation points [11], [12]. For an isotropic, homogeneous medium in a linear approximation and a transducer excited sinusoidally, using the SIR method we have in frequency domain:

$$p = j\omega\rho v_0 H(\vec{r}, k). \quad (1)$$

where ω is the angular frequency, v_0 is the constant normal velocity of the emitting transducer surface and ρ is the density of the medium. $\vec{r}$ is the reference vector to the study point, $H(\vec{r}, k)$ is the Fourier transform of the spatial impulse response $h(\vec{r}, t)$ of the system, $k = 2\pi/\lambda$, λ is the wave length and $j = \sqrt{-1}$. In this work, w is the axial coordinate starting at the "bottom" of the "bowl" formed by the transducer.

The geometrical focal gain can be expressed as [4]:

$$G_g = \frac{S}{\lambda A} \quad (2)$$

where S is "net area" of the active transducer surface, A is the radius of the sphere and the length of the focus.

Ultrasound intensity is computed in this study according the following expression:

$$\mathrm{I} = \mathrm{p}_0/2\rho\mathrm{c} \quad (3)$$

where p_0 is the amplitude of the acoustic wave and c is the velocity of propagating waves.

III. MATERIAL AND METHOD

There were considered single element and annular arrays transducers. For both type of transducers the focal distances were 100 mm, 80 mm and 60 mm. For the single element radiators the aperture radii were 32 mm, 31.25 mm and 30 mm, respectively. For the annular arrays radiators the aperture radii were 40 mm for all apertures. The working frequencies were 0.25 MHz, 0.5 MHz and 0.75 MHz for all possible combination of focal distances and aperture radii. The f-numbers of the apertures, understood as the focal length divided by the source diameter [4], were 1.25, 1.6 and 1 for the single element radiators and 1, 1.25 and 0.75 for the annular arrays radiators. The radii of the central hole were 10 mm for all simulated transducers. The characteristics of the acoustic medium were: ultrasound wave velocity 1450 m/s, characteristic acoustic impedance 1.3 MRayl and absorption coefficient α=0.63 dB/MHz-cm (fat [13]).

The expression (1) permits compute the acoustical pressure knowing$\mathrm{H}(\vec{\mathrm{r}}, \mathrm{k})$, in which the acoustic losses can be included. Given the absence of simple analytic solutions to calculate $\mathrm{H}(\vec{\mathrm{r}}, \mathrm{k})$ for the more general problems studied in this work, the Field II program was used to calculate this function [14]. All the calculations were processed in Matlab (Mathworks, Natick, MA).

Fig. 1 shows a diagram of the uniform spherical concave transducer with a central hold. "A" is the radius of the sphere and the geometrical focal length, a_1 is the diameter of the hole and a_2 is the diameter of the aperture. The figure also represents the more general geometry of the array transducers. Fig. 2 is a 2D representation of the annular spherical concave transducer with a central hold.

IV. RESULTS

Fig. 3 shows the linear focal shift effect for the single element transducers and Fig. 4 displays the same results for the annular array transducers. In both type of radiators there were comparatively considered the specified acoustic loss (α=0.63 dB/MHz-cm) and absence of this physical phenomenon.

In Fig. 5 it is shown the axial acoustic pressure distribution for a single element transducer (G_g= 9.83, f-number=1.25 and radius=32 mm) and annular array transducer (G_g= 8.54, f-number=1 and radius=40 mm). Both type of radiators had a focal distance of 80 mm and a working frequency of 0.375 MHz.

V. DISCUSSION AND CONCLUSIONS

From Figs 3-4 it can be observed that the focal shift effect is considerably reduced for the annular array transducers regarding the single element transducer for a given geometrical focal gain for low-to-moderately focused ultrasound transduces (up to $Gg = 10$). In addition and proportionally, the shift as a function of the losses in the acoustic medium is also significantly lower. This phenomenon can be considerably accentuated for tissues with a higher acoustic attenuation (e.g., muscle across fiber α=3.3 dB/MHz-cm [13]) or a transducer with a different geometry, as a l arger central hole. Additionally, in Fig. 5 it can be observed that the wide of the axial focal (3dB) of the simulated array ($Gg = 8.54$) is significantly reduce (about 50%) regarding the single element transducer ($Gg = 9.83$), even the wide of the axial focal increments with the decrement of the geometrical focal gain, for each type of these transducers. This can be important in numerous mild-hyperthermia applications where there is a need of concentrate the acoustic energy if the main lobe is extremely wide.

Axial grating lobes were also analyzed. In the worse case, the amplitude of the axial grating lobe showed a reduction 4.5 dB in the ultrasound intensity regarding the main lobe. If a better relation is needed, several techniques have been proposed in the literature to reduce the grating lobes, including by keeping the inter-element spacing close to one half of the acoustic wavelength and using apodization [15].

The results present in this work can be a contribution for a proper planning of many of the current mild-hyperthermia therapeutic applications, where a geometrically focused ultrasound transducer is used.

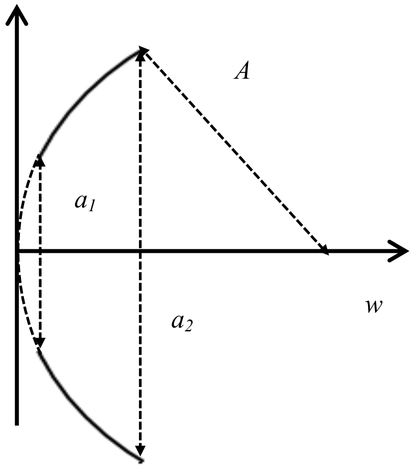

Fig. 1. Diagram of the uniform spherical concave transducer with a central hold. The figure also represents the more general geometry of the array transducers.

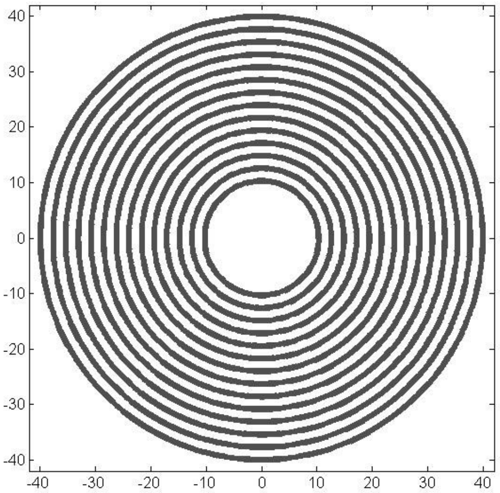

Fig. 2. 2D representation of the annular spherical concave transducer with a central hold.

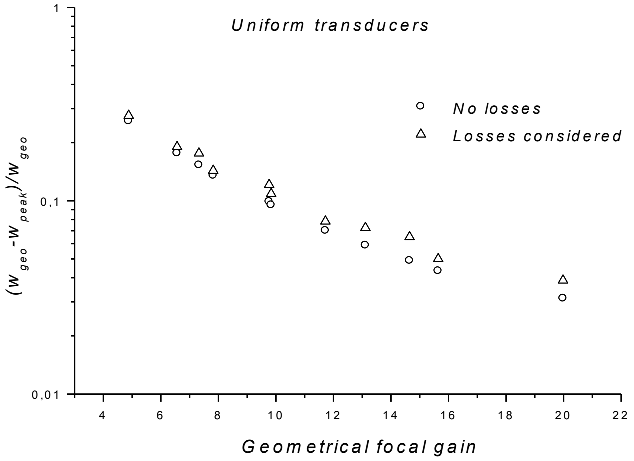

Fig. 3. A representation of the linear focal shift effect for the single element transducers simulated. For all radiators there were comparatively considered losses in the external acoustic medium and absence of this physical phenomenon.

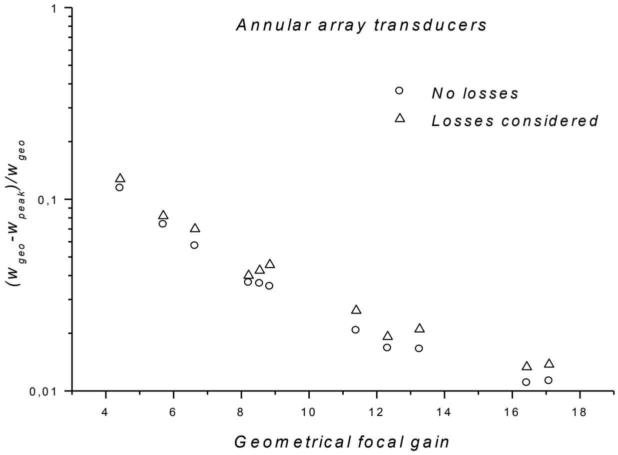

Fig. 4. A representation of the linear focal shift effect for the array transducers simulated. For all radiators there were comparatively considered losses in the external acoustic medium and absence of this physical phenomenon.

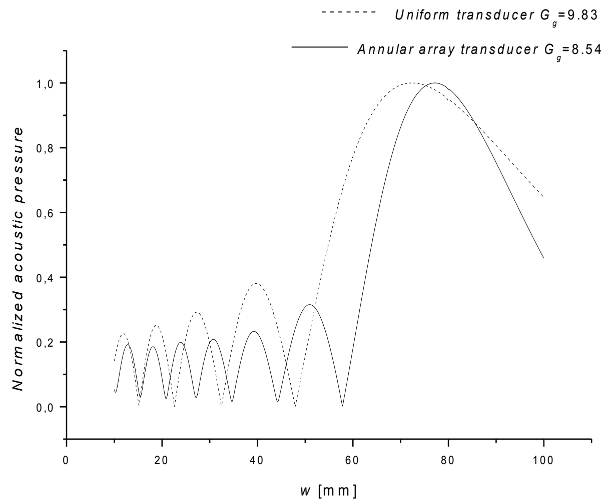

Fig. 5 A comparative representation of the wide of the axial focal zone (3dB) of the simulated transducer.

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