

Acoustic Field Comparison of High Intensity Focused Ultrasound by using Experimental Characterization and Finite Element Simulation

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Abstract: High Intensity Focused Ultrasound (HIFU) is used as a non-invasive technique of tissue heating and ablation for different medical treatments. This paper presents a quantitative comparison of HIFU acoustic fields experimentally obtained versus acoustic fields obtained by using Finite Element Method simulation. Two HIFU transducers were used: Onda Corporation[®] 2-30-100/4 and 2-20-20/2 with a nominal frequency of 4 MHz and 2 MHz respectively. Acoustic field characterization was realized in both transducers using water as a propagation medium. Also, simulations were developed considering the features of both transducers by using COMSOL Multiphysics[®] software. Finally, experimental and simulated acoustic fields were compared within the areas of highest concentration of ultrasound energy. Results show that the simulations achieve a diameter, area, and focal zone very close to that of the experimental data. Percentages above 80 % of similarity in the geometry which encloses the highest energy were obtained for both cases.

Keywords: acoustic field, characterization, focal zone, HIFU, simulation.

1. Introduction

High Intensity Focused Ultrasound (HIFU) is a technique currently used for different medical treatments such as thermal ablation, hyperthermia and bleeding control. Figure 1 shows a schematic drawing of HIFU treatment, the high powered focused beam is deposited causing tissue ablation at the selected zone. However, there are many challenges on the use of focused ultrasound; research and experimentation are made in order to optimize HIFU treatments.

Acoustic field characterization is important for the prediction of ultrasound bioeffects in different materials as tissues and for the development of regulatory standards for clinical HIFU devices [1]. This kind of characterization in

acoustic transducers is made by the measurement of the radiation patterns into the propagation space.

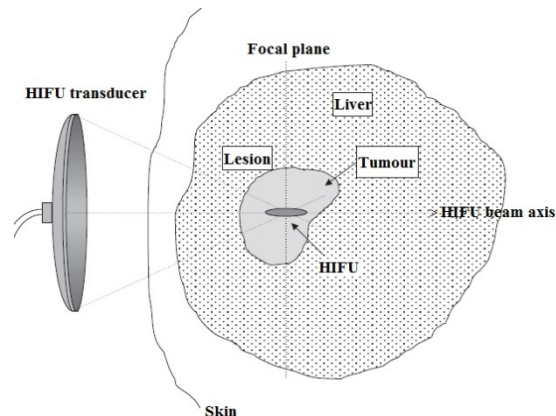


Figure 1. Schematic drawing of HIFU treatment in oncology [2]. Carcinogenic tumor is burned by focalized ultrasonic radiation.

Nowadays, simulations with Finite Element Method (FEM) are a helpful tool in different areas. A simulation model which mimics an experimental physical phenomenon could be a primary model to start different designs for improvement. Changes in the geometry, the materials, the boundaries and others over the primary model may result in new designs and better devices. Ultrasound devices and treatments can be improved as a result of a FEM simulation. This work presents a quantitative comparison between experimental and simulated acoustic fields of HIFU.

The pressure waveform in the acoustic field is assumed to be independent of the source power [1]. From this assumption, we can mimic a characterized acoustic field made at low power levels by using FEM simulation. Afterwards, the pressure data at FEM model can be extrapolated to higher output levels of the HIFU device for new simulation models.

2. Characterization of the HIFU transducers in water

Two HIFU transducers were considered to perform an acoustic characterization in order to compare the experimental with the simulated data: Onda Corporation® transducer 2-30-100/4 and 2-20-20/2 with a nominal frequency of 4 MHz and 2 MHz respectively. The acoustic field measurements were performed by using a wide-band hydrophone PZTZ44-0400. The transducer and the hydrophone were fixed and immersed in a tank filled of bi-distilled degassed water (Fig. 2). The hydrophone was placed in front of the transducer face by using a Scan 3.40 3D positioning system which has a minimum spatial resolution of 6.37 μm . Tektronix AFG3021B function generator drove the 2-30-100/4 HIFU transducer with a 3.90 MHz pulsed sinusoidal wave of 10 V_{pp} and repetition frequency of 10 Hz. In the other hand, the 2-20-20/2 was driven with a 1.965 MHz pulsed sinusoidal wave at the same amplitude and repetition. Data were stored in a PC by the Waveform software.

Measurements were done punctually close to the expected acoustic focus zone with the step resolutions shown in Table 1 for each transducer. All measurements were made taking the geometric center for each transducer as the reference center. Temperature characterization was from 22 °C to 25 °C.

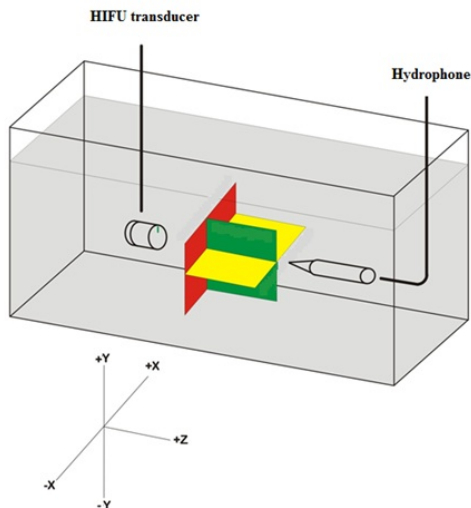


Figure 2. Representation of HIFU transducer characterization. Plane xz (yellow), plane xy (red), and plane yz (green) are shown.

Table 1: Spatial resolution used in acoustic field characterization.

	Step resolution		
	x [mm]	y [mm]	z [mm]
2-30-100/4	0.501	0.501	1
2-20-20/2	0.1016	0.1016	1

Acoustic pressure distribution is indirectly obtained from an electrical signal (peak-to-peak voltage) that is proportional to the pressure detected for the hydrophone.

3. Acoustic field simulations with COMSOL Multiphysics®

HIFU transducers are made with a concave face in order to focus the acoustic energy (Fig. 1). 2D axisymmetric geometry was defined in our model thus the concave face is considered as a symmetric geometry. The models to simulate the acoustic propagation through water consider the geometry shown in Fig. 3 and Fig. 4 for transducers 2-30-100/4 and 2-20-20/2, respectively. A concave geometry is set as pressure source in order to mimic a HIFU transducer face. Excitation frequency in the model was set as the same as the frequency of characterization.

The wave equation for harmonic problem is given by (1):

$$\nabla^2 p + k^2 p = 0, \quad (1)$$

Where p pressure (Pa), $k = \omega/c_s$, ω is angular frequency (rad/s) and c_s is ultrasound velocity in the medium (m/s). Propagation losses, scattering and attenuation are not considered in this equation [3].

The ultrasound wave velocity and density of the medium was set as 1500 m/s and 1000 kg/m³, respectively, which are considered as water properties at a temperature around 25 °C. Boundary conditions were set as water acoustic impedance in order to avoid reflections of the propagation wave. The model was solved in a steady state analysis with a mesh size of 1/5 times the wavelength.

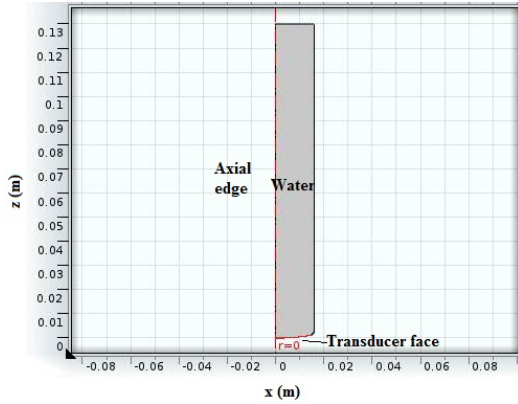


Figure 3. Geometry of the finite element model to simulate acoustic propagation through water (HIFU 2-30-100/4). The model boundaries are defined as water impedance in order to allow wave propagation and a half of concave geometry is defined as pressure source that mimics the concave transducer face.

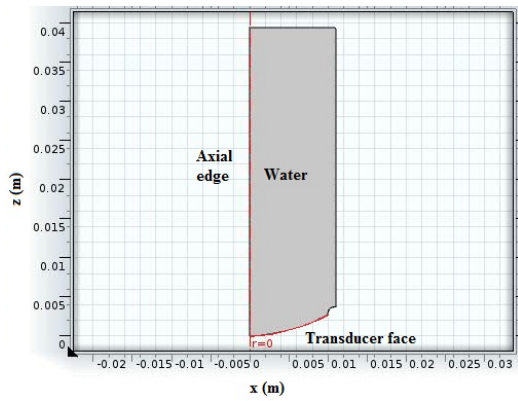


Figure 4. Geometry of the finite element model for HIFU 2-20-20/2. The model boundaries are defined the same way as the previous transducer.

4. Methods of comparison

4.1 Factor f_c

The factor f_c is defined as the ratio of the area intersected by both curves to the total area under both curves. With A and B as the areas under each curve the f_c can be expressed as:

$$f_c = \frac{A \cap B}{A \cup B}, \quad (2)$$

where f_c ranges from 0 if two signals have nothing in common and 1 if similarity increases [4].

Different power levels of HIFU beams can be enclosed in a delimited area to calculate the f_c between two acoustic fields. A power decay of -3 dB and -6 dB has been considered to calculate this factor. The factor f_c computes similarity in a way related to a correlation coefficient R .

4.2 Ellipsoidal shape ratio E_r

A typical focal region is ellipsoidal in shape, and its dimensions depend on the transducer frequency and focusing geometry [5]. Ellipsoid shape depends mainly of the dimensions on major and minor axis according to general equation of an ellipse. Thus, we can propose a ratio which involves minor and major axis, and compare it between ellipsoidal contours due to a HIFU beam. Equation (3) shows the ratio between two elliptical contours (E_1 and E_2).

$$E_r = \frac{\text{minor axis}_{E1} / \text{major axis}_{E1}}{\text{minor axis}_{E2} / \text{major axis}_{E2}}, \quad (3)$$

4.3 Euclidian distance point to point

Euclidian distance between points A (x_1, y_1) and B (x_2, y_2) in a plane is the length of the line segment which connect A and B points. It can be calculated as follows:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}. \quad (4)$$

A metric value is obtained from this length and it can use to compare how far two different ellipsoidal contours are each other.

5. Results

5.1 Transducer HIFU 2-30-100/4 comparisons

Data from experimental and simulated data were obtained and normalized to the maximum value found for each case in order to perform a quantitative comparison. Both acoustic fields show the acoustic pressure distribution in water. Figure 5 shows the same acoustic field characterized and simulated over three different planes in the space. COMSOL simulation gives a solution over the whole domain geometry, but we can delimit the simulated data at the same

dimensions as the experimental using MATLAB®.

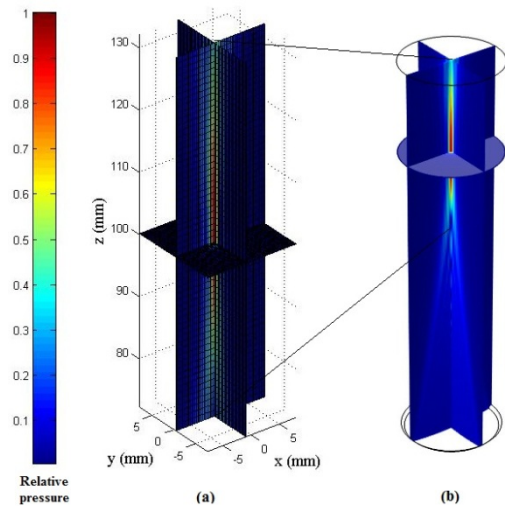


Figure 5. This image shows the three planes (xz , xy and yz) that were obtained from the 2-30-100/4 transducer. Experimental acoustic field (a) and Simulated acoustic field (b). Experimental characterization was only made along the transducer focal zone of interest as is observed.

Figure 6 and Figure 9 show the acoustic planes along axis xz and xy respectively with relative similarity. Transducer manufacturer gives a focal length of 100 mm as a nominal value. Table 2 shows the experimental and simulated focal zone obtained compared to the nominal.

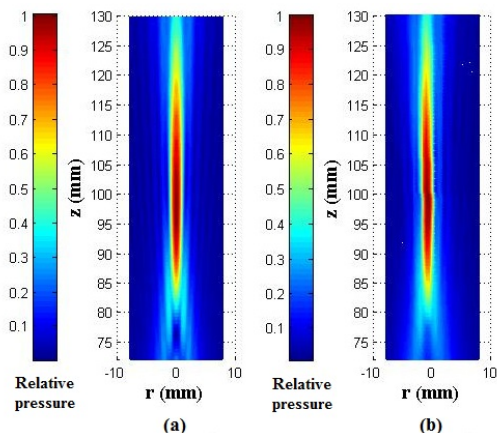


Figure 6. Acoustic field distribution along propagation plane xz for FEM simulation model (a) and measured data (b). Transducer focal area for both cases is located about 100 mm from the transducer concave face along axis z .

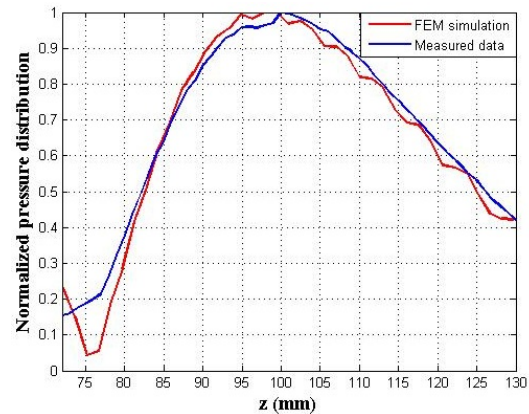


Figure 7. Comparison of normalized pressure distribution between FEM simulation and measured data. Distribution along propagation axis z referred to the maximum value point for each case.

A pressure distribution and the focal length along axis z can be appreciated at Fig. 7 with the highest pressure values around 100 mm as can be seen.

Table 2: Comparison of focal lengths obtained versus the nominal value in transducer 2-30-100/4.

Nominal focal length	Experimental focal length	Simulated focal length
[mm]	[mm]	[mm]
100	100.1 ± 0.23	98.64

Different pressure changes have been enclosed in a specific area by a contour. Figure 8 and Figure 10 show an overlapping of contours between power decay at -3 dB and -6 dB. Similar areas were obtained and the corresponding values for the areas are shown in Table 3. A displacement on the experimental acoustic field is observed from the geometric center of the transducer; the shift is -1.03 mm along axis x and 0.51 along axis y . The displacement probably is due to the no ideal construction of the HIFU transducer and the minimum errors in the measurement method. A summary of comparison values is shown in Table 4, it includes the factor f_c , the ellipsoidal shape ratio E_r and the Euclidian distance between the contours previously mentioned in planes xz and xy . The f_c was calculated by centering the experimental field with the simulated only for this transducer.

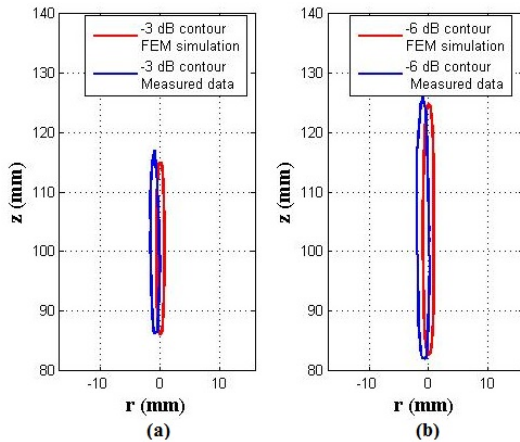


Figure 8. Comparison of signal decrease between FEM simulation and measured data when using pressure contours. Contours enclosing signal values above -3 dB (a) and -6 dB (b) of relative pressure are superimposed respectively. The mean Euclidian distance is 0.72 ± 0.47 mm between -3 dB contours and 0.83 ± 0.28 mm between -6 dB contours.

Table 3: Enclosed area for pressure contours at -3 dB and -6 dB through xz and xy planes.

	Area xz [mm ²]		Area xy [mm ²]	
	-3 dB	-6 dB	-3 dB	-6 dB
Experimental	32.07	68.30	1.22	2.55
Simulation	30.45	63.15	1.42	2.63

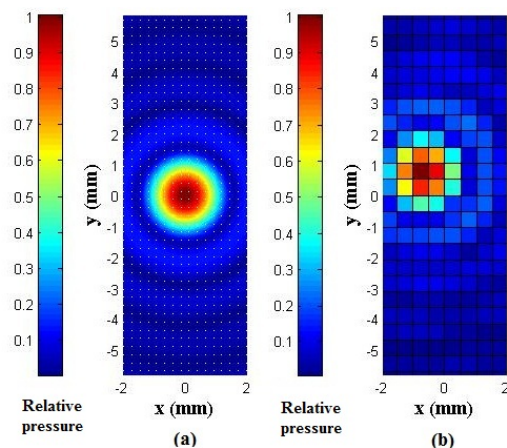


Figure 9. Acoustic field of FEM simulation model (a) and measured data (b) along xy plane (cross-sectional plane). Both planes are xy slices at 100 mm along axis z .

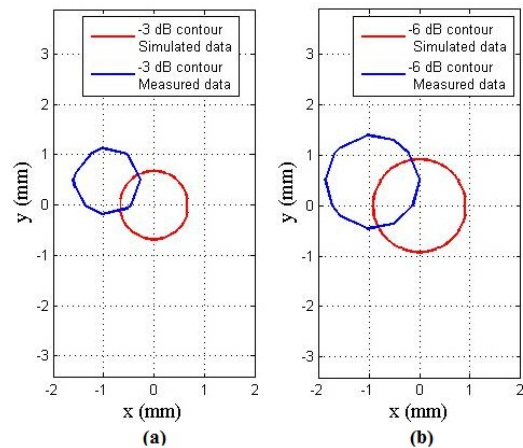


Figure 10. Contours enclosing signal values above -3 dB (a) and -6 dB (b) of relative pressure are superimposed respectively. Focal diameters simulated and experimental of 1.83 mm and 1.86 mm were obtained respectively.

Table 4: Comparison values between experimental and simulated contours at -3 dB and -6 dB.

	Factor f_c [%]	Ellipsoidal ratio E_r [%]	Euclidian distance [mm]
-3 dB xz	94.9	80.5	0.72 ± 0.47
-6 dB xz	92.4	82.9	0.83 ± 0.28
-3 dB xy	85.9	93.7	0.63 ± 0.34
-6 dB xy	96.9	96.1	0.62 ± 0.31

The shape comparison values are above 80 % both for plane xz and xy while the Euclidian distance shows a difference in distance between contours around 0.70 mm.

6.2 Transducer HIFU 2-20-20/2 comparisons

Results for HIFU 2-20-20/2 were obtained in a similar way as the previous shown. Figure 11 and Figure 14 show the acoustic field in xz and xy respectively. Changes in amplitude along the propagation axis z can be appreciated at Figure 12 with the highest pressure values between 20 mm and 21 mm. Table 5 shows the focal length values obtained and it compares to the nominal focal length which is 20 mm.

Contours for power decay at -3 dB and -6 dB also were made. Contours at plane xz are shown in Figure 13 and contours at plane xy are shown in Figure 15. This overlapped contours show a very high similarity as one showed for the 2-30-100/4 transducer. A summary of the areas

obtained and comparison values are show in Tables 6 and 7. Factor f_c percentages are above 60 % and values of ellipsoidal shape ratio are above 80 %. A minimum difference of distance between each contour is given by the Euclidian distance which shows values around 0.25 mm for contours in xz plane and values around 0.1 mm for contours in xy plane.

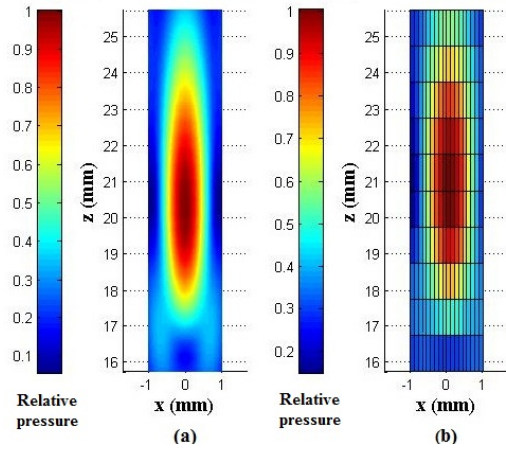


Figure 11. Acoustic field of FEM simulation model (a) and measured data (b) along xz plane. Transducer focal area for both cases is located about 20 mm from the transducer concave face along axis z .

Table 5: Comparison of focal lengths obtained versus the nominal value in transducer 2-20-20/2.

Nominal Focal length [mm]	Experimental focal length [mm]	Simulated focal length [mm]
20	20.72 ± 0.24	20.56

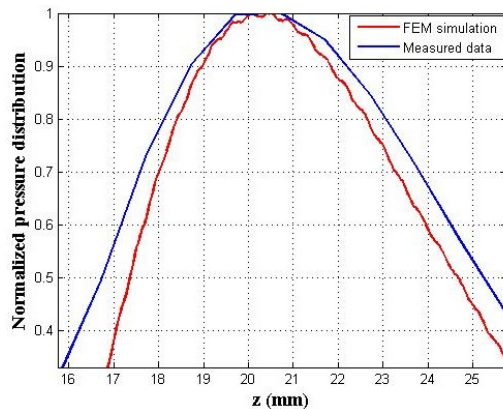


Figure 12. Comparison of normalized pressure distribution between FEM simulation and measured data. Distribution along propagation axis z referred to the maximum value point for each case.

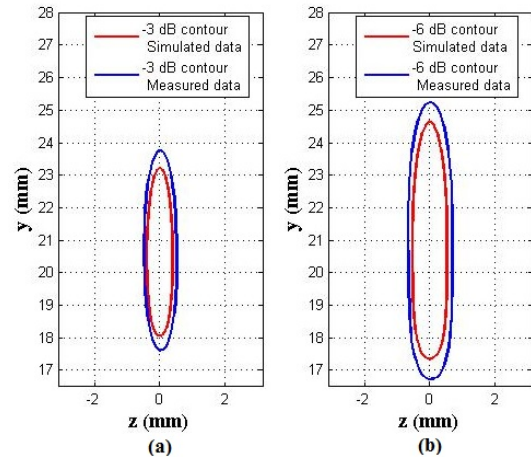


Figure 13. Contours enclosing signal values above -3 dB (a) and -6 dB (b) of relative pressure are superimposed respectively. The mean Euclidian distance is 0.24 ± 0.14 mm between -3 dB contours and 0.30 ± 0.16 mm between -6 dB contours.

Table 6: Enclosed area for pressure contours at -3 dB and -6 dB through xz and xy planes.

	Area xz [mm ²]		Area xy [mm ²]	
	-3 dB	-6 dB	-3 dB	-6 dB
Experimental	4.86	9.73	0.72	1.39
Simulation	3.22	6.42	0.48	0.91

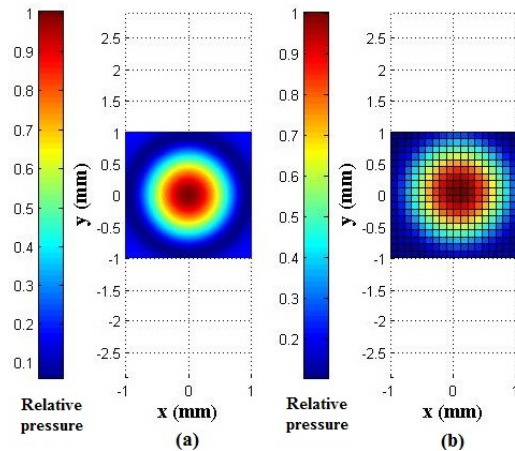


Figure 14. Acoustic field of FEM simulation model (a) and measured data (b) along xy plane (cross-sectional plane). Both planes are xy slices at 20 mm along axis z .

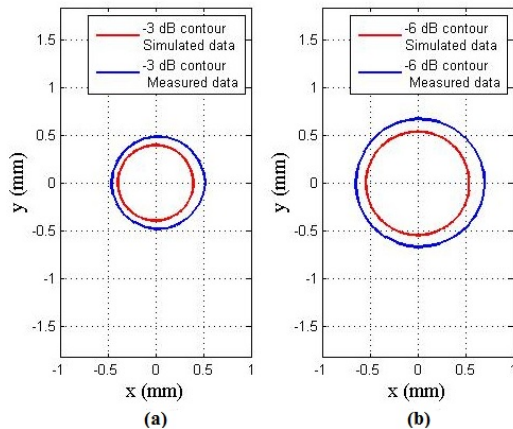


Figure 15. Contours enclosing signal values above -3 dB (a) and -6 dB (b) of relative pressure are superimposed respectively. Focus diameters at -6 dB for simulated and experimental contours: 1.07 mm and 1.34 mm were obtained respectively.

Table 7: Comparison values between experimental and simulated contours at -3 dB and -6 dB.

	Factor f_c [%]	Ellipsoidal ratio E_r [%]	Euclidian distance [mm]
-3 dB zx	66.1	91.1	0.24 ± 0.14
-6 dB zx	66.0	86.4	0.30 ± 0.16
-3 dB xy	66.5	97.7	0.08 ± 0.01
-6 dB xy	65.3	98.7	0.13 ± 0.01

7. Conclusions

The acoustic fields in water of the two HIFU transducers were measured and simulation models were carried out in similar conditions. A high level of similarity was obtained between characterized and simulated acoustic fields. The percentages of similarity are above 80 % in the transducer HIFU 2-30-100/4 and the percentages of similarity are above 60 % in transducer HIFU 2-20-20/2. A displacement in the axis x and y was obtained for the experimental acoustic field of the transducer 2-30-100/4, but it is probably due to the no ideal geometry of manufacturing in the transducer. Despite of the shift, we have obtained a great similarity in the HIFU beam. This is a great approach to start new models that involve the same HIFU transducers in applications as cancerous tissue ablation.

The area of HIFU ultrasound applications has shown great challenges and FEM simulation is a

helpful method to simulate ultrasound propagation waves and heating.

8. References

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9. Acknowledgements

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