COBEM-2017-2924
MANUFACTURING OF MULTI-ELEMENT PIEZOELECTRIC TRANSDUCER FOR USE IN ULTRASOUND ELASTOGRAPHY

Breno Spinelli Coelho
Chi-Nan Pai
Polytechnic School of the University of Sao Paulo, Department of Mechatronic and Mechanical Systems Engineering, Sao Paulo, Brazil
breno.spinelli200@gmail.com, chinan.pai@usp.br

Abstract. *Ultrasound elastography is a new imaging technique to estimate the tissue elasticity. In this technique, an external mechanical excitation source is used to generate the vibration of the target, while an imaging transducer is used to track the shear waves speed that is correlated to the elasticity. The objective of this work is to develop an ultrasound transducer to be used as the excitation source. An ultrasonic transducer with 64 elements was built by using 5 MHz piezoelectric ceramic. A multi-element transducer was chosen to concentrate the mechanical energy at one point, avoiding the undesired effects on the adjacent tissues. Five different samples of mixture of epoxy and tungsten powder was tested to choose the best attenuation layer on the back side of the ceramic. A layer of epoxy and alumina was placed on the front side for better transmission of the mechanical wave. The transducer housing and fabrication jigs were designed and fabricated by using 3D printer to decrease the prototyping time. As a result, the proportion of 30% in mass of tungsten powder was chosen because of its good acoustic impedance (3.47 $MRayls$) and acceptable attenuation (18.10 dB/cm) properties. Each element showed adequate signal transmission. Our next step would be applying the ultrasound wave focus technique and higher power to generate the vibration of the target in a phantom.*

Keywords: ultrasound, imaging, medical, ceramics.

1. INTRODUCTION

Many pathologies such as cancer, atherosclerosis and hepatic cirrhosis change biological tissue's elasticity. For example, in case of hepatic cirrhosis the hepatic tissue turns stiffer, so standard diagnosis procedures can easily find abnormalities. Nowadays, these kinds of diseases are diagnosed by puncture biopsy, a technique that uses a needle to cut off a sample of the sick tissue for analysis. Thus it is an invasive method that causes injuries in patients.

Another sort of examination is palpation, which consists in the pressure provided by the doctor's hand over the tissue (Bickley and Szilagyi (2012)). Such a method is an important part of the physical examination. However, palpation is a qualitative method and the interpretation of the results depends on the experience of the medical doctor, even though it is not an invasive technique. In order to provide a quantitative method for the evaluation of tissue elasticity, ultrasound elastography has been researched (Dewall (2013)).

Quantitative tissue elasticity can be estimated by dynamic elastography techniques. To apply these techniques, an external mechanical excitation source can be used to generate ultrasound waves in tissues. These waves have short periods (approx. 262 μs), high amplitude and must be focused only on the target tissue. The tissue vibration generates shear waves that can be tracked by ultrasound transducers (Friedrich-Rust et al. (2012)). If we assume that the tissue is isotropic and incompressible, the shear wave speed is proportional to the square root of the tissue elasticity. One way to obtain the transient mechanical excitation of the tissue is by using the acoustic radiation force, which can also be provided by an ultrasound transducer (Bickley and Szilagyi (2012)).

Acoustic radiation force can be generated by a mono-element transducer or a multi-element transducer (Andrade (2006)). When using a multi-element transducer, each element sends a small amount of energy, and all of them are added in the focus point, which can be reached by controlling the periodicity and intensity of electric pulses sent from the ultrasound machine to the elements of the transducer. Therefore, a high level of energy can only be found in the focus point, and there is no damage to the tissues between the target and the transducer.

In this work, we describe the development and evaluation of a multi-element piezoelectric ultrasound transducer to apply the acoustic radiation force.

2. EXPERIMENTAL PROCEDURE

Ultrasound waves are scattered and their energy are decreased by the increase of amount of tissue between the target and the transducer. So, it is necessary to find some way to concentrate the mechanical energy provided by the piezoelectric ceramic. It is possible by dividing the ceramic into several smaller elements, so each element can be controlled to focus its ultrasound wave on the desired point, far from surface.

In terms of architecture, mono-elements and multi-elements transducers are similar. Basically, a transducer contain a core, composed of the ceramic, a damping layer behind the ceramic and a matching layer in front of it, signal cables connected to the elements of the ceramic to conduct the electric pulses from the pulser, and a housing to protect and to assemble all the components.

Considering the architecture above described, a 64-element ultrasound transducer will be manufactured with a rectangular, 5 MHz piezoelectric ceramic (PZT37, Ferroperm Piezoceramis A/S, Denmark) (Andrade (2006); Shung and Zipparo (1996)) and tested under water. The development of the main layers of the transducer's architecture will be detailed in the following sections. Similar procedures were used by Buiochi *et al.* (2012)

2.1 Damping layer characterization

The acoustic impedance of air and PZT is very different, and this difference creates an reflection interface which causes the ultrasound wave generated by PZT to return back to ceramic, interfering in the propagation of the ultrasound wave.

In order to avoid this interference, a damping layer, called backing, is required to propagate and to attenuate the backward ultrasound waves, and a matching layer in front is required to propagate and to transmit the waves to the target. In this work, these backing layers were made of tungsten powder and a mixture of epoxy resin and its hardener (SQ2001 and SQ3154, 2:1).

In order to improve backing layer's performance, four samples of backing layer were manufactured with the following proportions of tungsten: 0% in mass, 30% in mass, 26% in volume and 30%, and their acoustic properties measured and compared to the ones in water. Table 1 shows quantities of epoxy resin and tungsten in each sample.

Table 1. Backing composition

Sample	SQ2001 (g)	SQ3154 (g)	Tungsten (g)
Pure	12.8	6.4	0
30% in mass	12.8	6.4	5.8
26% in volume	14.6	7.3	133.6
30% in volume	12.8	6.4	100.2

Figure 1 shows a schematic of the measurement procedure. The samples were put between two transducers (Alpha transducer, Aerotech, USA), one of them emitted 5 MHz waves from a wave pulser (5072PR, Olympus Co., E.U.A.) to pass through the sample and the other received the wave and sent to the oscilloscope for analysis (Franco *et al.* (2005)).
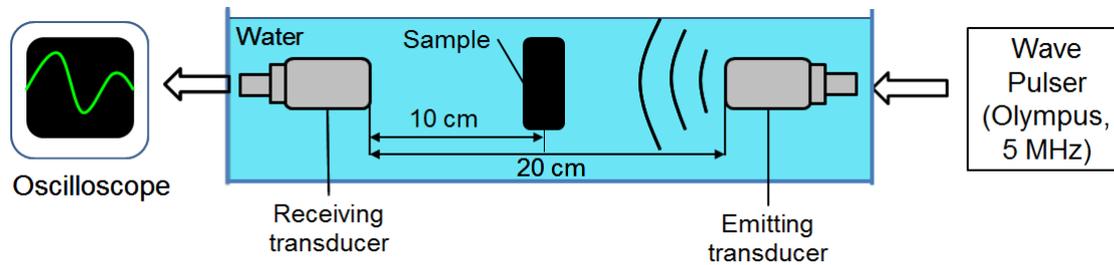

Figure 1. Schematic of the experimental setup to characterize the backing samples

By using the measurement of the wave amplitude and the traveling time Δt, along with the Eq. (1 to 4) (Andrade (2006); Franco *et al.* (2005)), the wave velocity inside the sample (c_b), the sample's acoustic impedance (Z_b) and the sample's attenuation (α) can be calculated. In these equations, A_w is the wave amplitude without the sample, A_s is the wave amplitude with sample, d is the sample thickness, T_t is the total transmission coefficient, ρ is the sample density, c_w is the sound velocity in water and Z_w is the acoustic impedance of water. The sample with good acoustic impedance and attenuation will be used in the backing layer.

$$\alpha(dB/m) = \frac{20log(\frac{A_w}{A_s}T_t)}{d} \tag{1}$$

$$Z_b(\frac{kg}{m^2 s}) = \rho\, c_b \tag{2}$$

$$c_b(m/s) = \frac{c_w}{1 + \frac{\Delta t\, c_w}{d}} \tag{3}$$

$$T_t = \frac{4\, Z_b\, Z_w}{(Z_b + Z_w)^2} \tag{4}$$

2.2 Transducer core

Figure 2 shows the schematics of the transducer core, which is responsible for the emission of the ultrasound wave. The PZT ceramic is 21 mm in length and 10 mm in width. It was cut into 64 elements by using a precision automatic dicing saw (DAD322, Disco Corp., Japan). Therefore, each element is 10 mm in length and 0.3 mm in width.

Two printed circuit boards, each with 32 connector, were glued to the ceramic by using conductive epoxy (Circuit-Works Conductive Epoxy, Chemtronics, USA), as shown in Fig.2B. These boards were required to facilitate the welding process of the electric wire. Therefore, instead of welding the wires directly on the elements, they were welded on the circuit boards.The circuits must be fixed so that the tracks should stuck alternately on each element (Fig.3) when they were cut.
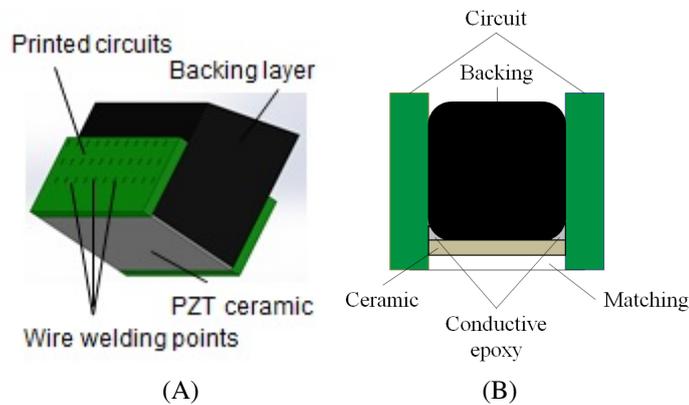

(A) (B)
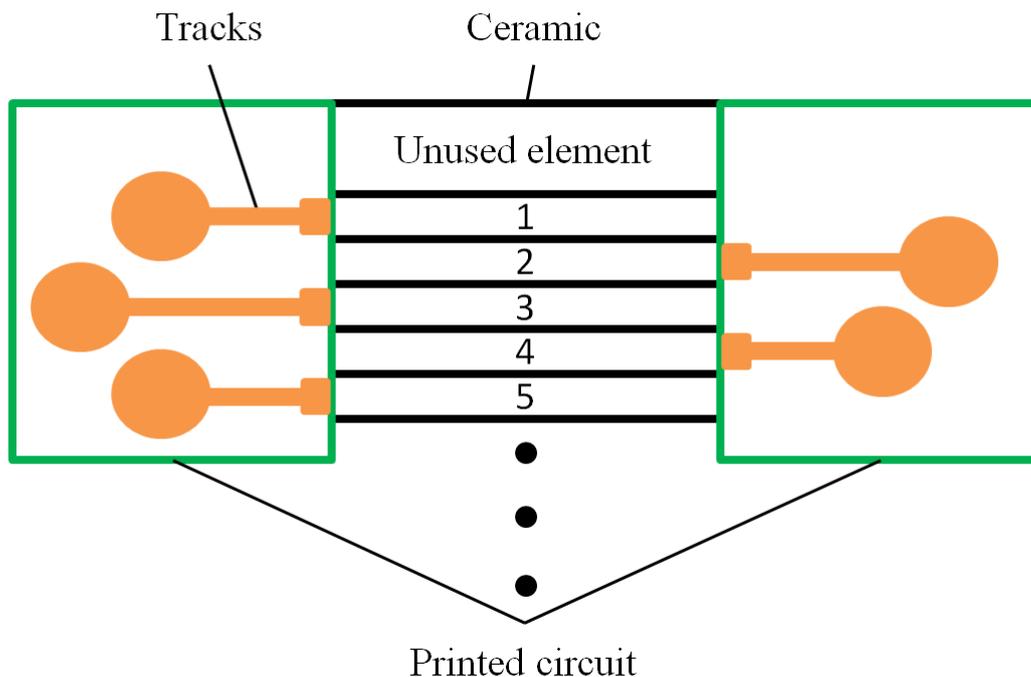Figure 2. (A) PZT ceramic core; (B) core with conductive epoxy

Figure 3. Schematic of elements connection with the circuit's buffer

2.2.1 Matching layer

The matching layer is a mixture of epoxy (the same from backing manufacturing) and alumina dust. Equation 5 was deducted to calculate its thickness and it takes into account that thickness shall be 1/4 of wave length inside the matching layer (Hendee and Ritenour (2003)). In this equation, Z_m is the matching layer's acoustic impedance in $Rayls$, which is calculated from Eq.6, where Z_c is the ceramic's acoustic impedance and Z_w is the water's acoustic impedance, f is the ceramic's frequency in Hz, σ is the ratio between total mass of matching and mass of alumina, δ is the ratio between mass of SQ2001 and mass of SQ3154, d_e is the SQ3154 density, d_r is the SQ2001 density and d_a is the alumina density.

$$e_m(\sigma) = \frac{Z_m}{4f\sigma} \frac{(\delta\, d_e + d_r)}{d_e\, d_r} \frac{(\sigma - 1)}{(\delta + 1)} + \frac{Z_m}{4f\sigma\, d_a} \tag{5}$$

$$Z_m = (Z_c\, Z_w^2)^{1/3} \tag{6}$$

From Eq. 6, a $Z_m = 3.4 MRayls$ was found. By assuming δ equal to 2 and choosing $\sigma = 5$, the matching layer's thickness calculated was $e_m(5) = 0.13mm$. Thus, 0.4 g of alumina, 1.06 g of SQ2001 and 0.54 g of SQ3154 were used to manufacture 2 g of matching layer.

2.3 Transducer housing

Figure 4 shows the housing designed to assemble all the parts of the transducer. A component denominated core holder was designed to organize the signal cables of the core, before assembly in the housing, as shown in Figure 4A. It is also important to adjust the perpendicularity of the front face of the ceramic with respect to the length of the transducer housing, and to adjust the distance between the front face of the ceramic and the housing.

Inside the transducer housing, the signal cable was fixed in a zigzag pattern by the structure shown in the Figure 4A. This fixation pattern works as a cable gland, which avoid mechanical stress on the welding points.

Figure 4B shows the transducer closed. A component named glove was used as a temporary jig to maintain the housing closed during adjustments. Once all is set, both parts of the housing were glued together.
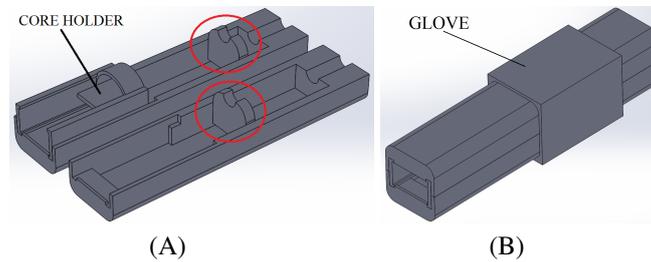

CORE HOLDER   GLOVE

(A)   (B)
Figure 4. (A) Open housing with core holder and (B) closed housing

2.4 Evaluation of the transducer

Figure 5 shows a schematic of the procedure for the evaluation of the transducer. It was put 5 cm away from a 5 MHz receiving transducer (Alpha transducer, Aerotech, USA). The same wave pulser used to characterize the backing samples was used to stimulate the 64 elements, one at a time, this time with a 15 dB gain and a 100 $Volts$ amplitude wave from the pulser. The signal from the receiving transducer was captured by an oscilloscope.

Oscilloscope   Water   5 cm   Receiving transducer   Transducer   Wave Pulser (Olympus, 5 MHz)
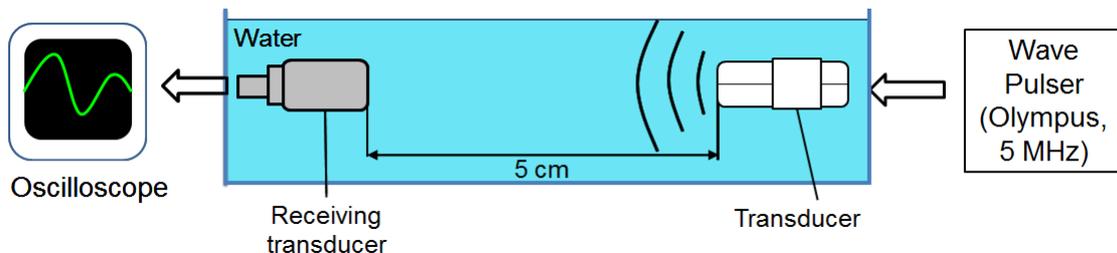
Figure 5. Schematic of the transducer evaluation procedure

3. RESULTS AND DISCUSSIONS

Table 2 shows the values of velocity, acoustic impedance and attenuation for each backing sample. For the 30% in mass sample, the results were considered good because the values of attenuation and impedance were satisfactory and the

quantity of tungsten used was very low. Therefore, the proportion of 30% in mass was chosen to be used to manufacture the backing layer.

Table 2. Sample's characteristics values

	Velocity (m/s)	Acoustic impedance (MRayls)	Attenuation (dB/cm)
Water	1480	1.48	-
Pure	2585.40	3	9.13
30% in mass	2380.27	3.47	18.10
26% in volume	1553.89	7.57	28.18
30% in volume	1588.51	8.42	29.69

Figure 6 shows the final structure after the printed circuits were fixed. The ceramic was fixed in a base with Kapton tape and the printed circuits were positioned beside the ceramic with "L" supports (Fig.6B) so that the epoxy could be set. This procedure was hand made and demands some positioning precision because the circuits should stand 90 degrees with the ceramic. Moreover, the pieces should be handle carefully because the joint between ceramic and circuit was very fragile.

Figure 6. Printed circuits and ceramic fixed by conductive epoxy

Figure 7A and B show results from procedures of matching and backing manufacture respectively. "L" supports were added (Fig.7A) to avoid backing leak, because it is fluid by the time it is set. The matching layer (Fig.7B) didn't have an equal distribution along the ceramic surface because of a slight slope of the core during the matching curing. Moreover, in order to enhance the transducer's performance, the bubbles inside the matching and backing layers were removed by a vacuum pump, some remained inside of them though.
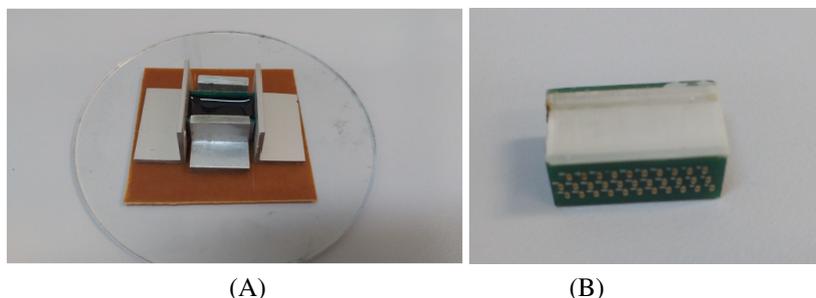

(A)   (B)

Figure 7. (A)Backing added in the transducer; (B)Matching added in the transducer

Figure 8 shows the transducer with welded cables and ready for tests. The zigzap pattern inside the housing worked as cable gland, and the cable was firmly fixed in the transducer housing, avoiding the mechanical tension on the welding points.

The signal amplitude of some of the tested elements, namely, 8, 17, 36 and 58, are shown, respectively, in Fig.9A, B, C and D. The amplitude varied from 0.2 $Volts$ to 0.7 $Volts$, in a random pattern along the array of the elements.
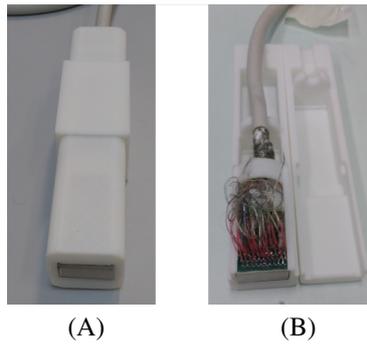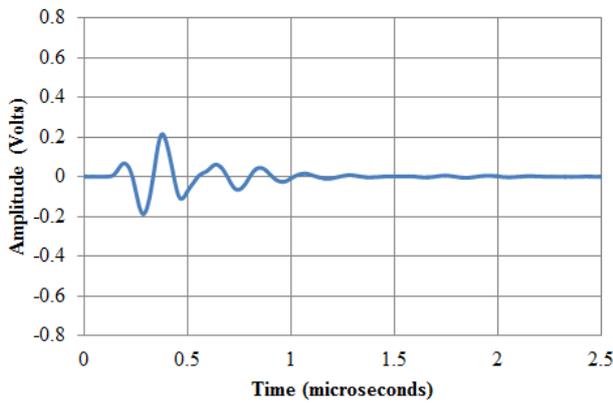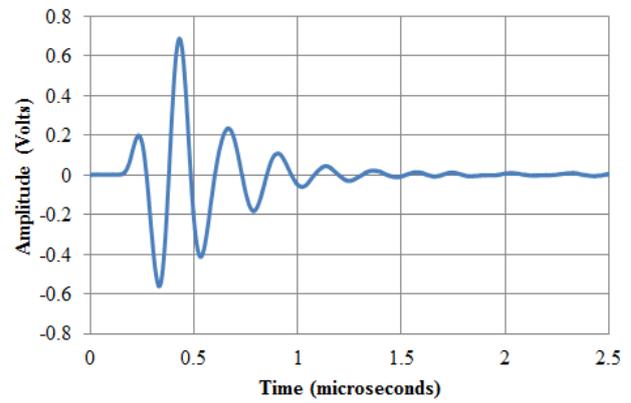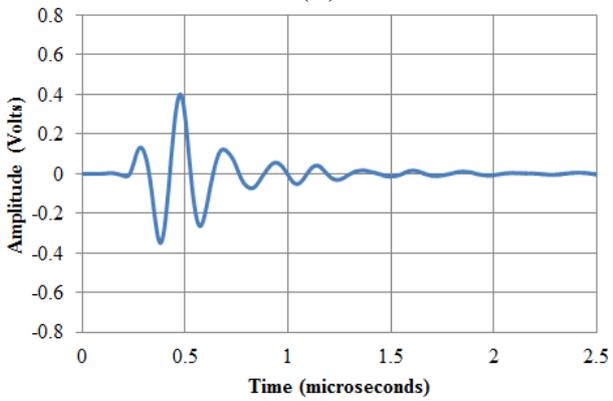
(A) (B)

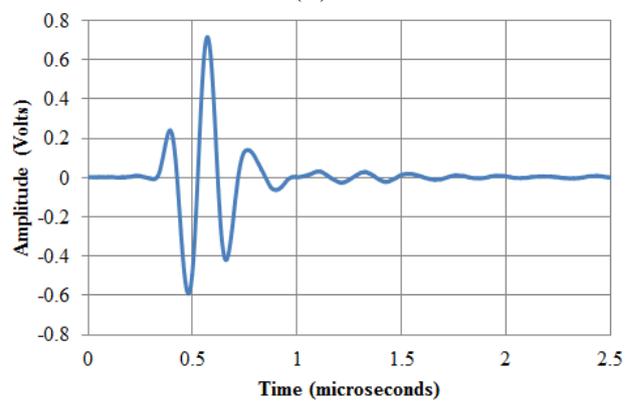Figure 8. (A) Closed housing; (B) open housing

(A) (B)

(C) (D)

Figure 9. Signal from elements (A) 8, (B) 17, (C) 36 and (D) 58

These differences may be explained by the manufacturing errors. The air bubbles in the matching and the backing layer may interferer in the vibration of the elements; The gaps between each elements, which were supposed to be filled with epoxy, may have air bubbles as well; And the matching layer was not evenly distributed on the surface of the transducer, and it may decrease the transmission of some of the elements.

Normally the band frequency of the transducers is measured in order to observe the bandwidth of the transducer. However, in our case, we are going to use the transducer only as emitter, and it will work only at 5 MHz. Therefore, there is no need to evaluate the bandwidth of the transducer.

4. CONCLUSIONS

The development of ultrasound transducers for medical imaging is a high precision process. However, it has many handmade steps, so human mistakes are unavoidable during the manufacturing. Thus, this work demands many practical skills besides theoretical knowledge.

An multi-element ultrasound transducer was fabricated. There signal amplitude varies from 0.2 to 0.7 $Volts$. As next step, we are going to use the wave focus technique and higher power to apply acoustic radiation force on the target.

5. ACKNOWLEDGEMENTS

6. REFERENCES

Andrade, M.A.B., 2006. *Análise de materiais piezelétricos compósitos para aplicações em transdutores de ultra-som*. Ph.D. thesis, University of São Paulo.

Bickley, L. and Szilagyi, P.G., 2012. *Bates' guide to physical examination and history-taking*. Lippincott Williams & Wilkins.

Buiochi, F., Oliveira, T.F., Buiochi, E.B. and Adamowski, J.C., 2012. "Processo de construção de trasndutores ultrassônicos matriciais lineares". *CBEB 2012 - XXIII Congresso Brasileiro em Engenharia Biomédica*, pp. 1–5.

Dewall, R.J., 2013. "Ultrasound elastography: principles, techniques, and clinical applications". *Crit Rev Biomed Eng*, Vol. 41, No. 1, pp. 1–19.

Franco, E.E., Andrade, M.A.B., San Miguel, J.E., Buiochi, F. and Adamowski, J.C., 2005. "Determination of the acoustic properties of tungsten/epoxy and tungsten/polyurethane composites using ultrasonic transmission technique". In *Proceeding of COBEM*.

Hendee, W.R. and Ritenour, E.R., 2003. *Medical imaging physics*. John Wiley & Sons, 4th edition.

Shung, K.K. and Zipparo, M., 1996. "Ultrasonic transducers and arrays". *IEEE Engineering in Medicine and Biology Magazine*, Vol. 15, No. 6, pp. 20–30.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.