RADIATION FORCE BALANCE AS A RESOURCE TO ESTIMATE ATTENUATION OF HIGH POWER CONTINUOUS ULTRASOUND FROM INSERTION LOSS MEASUREMENTS

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Abstract: Insertion loss (IL) is the difference between transmitted and received energy when a medium is interposed between transmitter and receiver. Radiation force balance (RFB) is a device that enables the measurement of the power output physiotherapeutic ultrasound equipment. The present work describes a method of measuring IL by comparing the power measured by a RFB before and after the insertion of a sample tissue mimicking material between transducer and balance target. Four samples were prepared to test the method (PVCP, Silicone, PVCP + 1% graphite and Epoxy). The attenuation coefficient of the samples is obtained by transmission-reception (TR) method. No significant difference between the IL at different powers for samples of PVCP and Silicon was observed. Differences were found for PVCP + 1% graphite and epoxy samples. This work raises the point that is not possible to transpose attenuation measurements at low power to high power applications as it found differences between both methods of obtaining the attenuation coefficient: Radiation Force Balance and Transmission Reception Method.

Keywords: Insertion loss, Attenuation, Radiation Force, Tissue Characterization.

Introduction

Tissue characterization by Ultrasound (US) has a direct application in medical diagnostics as it consists in finding properties that enable to detect alterations in a particular tissue or discriminate different tissues [1]. Ultrasound provides an interesting option for such characterization because it is a non-ionizing radiation, is an easy handling and cost effective technique and based on medium mechanic properties [1, 2]. There are four ultrasonic properties usually employed in tissue characterization: propagation velocity, impedance, scattering and attenuation [3, 4]. Despite the fact that attenuation represents a combination effect of absorption and scattering, there are specific methods of measuring each of them separately [5, 6]. The most common method for attenuation evaluation is based on the measurement of the pressure decrease along the direction of propagation obtained by either pulse-echo or transmission-reception (TR) [7]. The latter method requires knowledge of the acoustic field distribution and a precise alignment between transmitter and receiver.

In literature, there are reports on the use of radiation force to measure the intensity [8, 9] and absorption of ultrasound in a medium [10, 11]. The experiments began by using a torsion pendulum or balance attached to a disc or sphere moved in the presence of an ultrasonic beam. However, studies showed limitations that affected the accuracy of the method [12].

Radiation force (RF) is a phenomenon that can be used to measure the power output of US equipment employing a sensitive balance. The force exerted on the radiation force balance (RFB) is proportional to the radiated power [8]. It does not require the knowledge of the acoustic field and is independent of the frequency. The present work uses a method to estimate the insertion loss by comparing the power measured by a RFB before and after the insertion of a sample tissue between the transducer and the balance target. In addition, we discuss how the insertion loss can approach the attenuation estimation. As it is based on a principle distinct of the traditional attenuation measurement, it provides a possibility of checking its consistency.

Materials and methods

A schematic representation of the balance working principle is presented in Figure 1. An US Transducer is aligned towards a conical target located inside recipient filled with water. When this transducer is excited, its irradiation exerts in the target a force proportional to the radiation power (Figure 1A). The method here proposed to estimate insertion loss is shown in Figure 1B. Interposing a sample of the studied material between the transducer and the target will reduce the energy reaching the target. This reduction is a function of the reflection and transmission coefficients (that can be calculated) as well as of the attenuation in the sample material.

Four samples were prepared to test the method. Sample number 1 was made with pure Polyvinyl Chloride Plastisol (PVCP), sample number 2 was made with PVCP loaded with graphite powder (1% in weight), sample number 3 was made with Silicone and sample number 4 was made with Epoxy (Figure 2). All samples were disk shaped having 4.42 cm diameter and thicknesses as in Table 1.

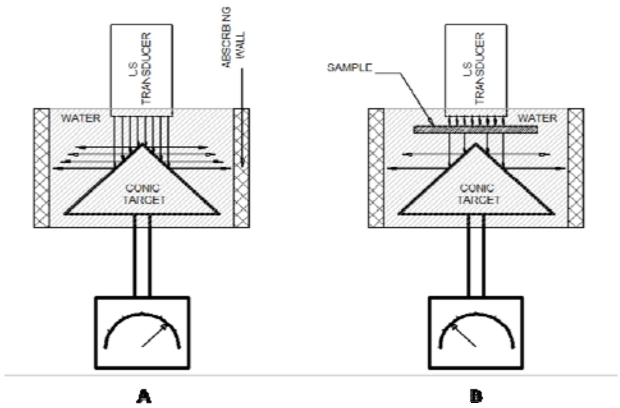

Figure 1: Schematic representation of RFB. (A) Without sample; (B) With sample. The difference between the power measured in A and B is proportional to the material sample insertion loss.

Table 1: Sample thicknesses

Sample	Thickness	Standard Deviation
PVCP	0.473	0.021
Silicone	0.420	0.008
PVCP + graphite	0.471	0.012
Epoxy	0.445	0.007

Thickness: Average value of 10 measurements (cm)

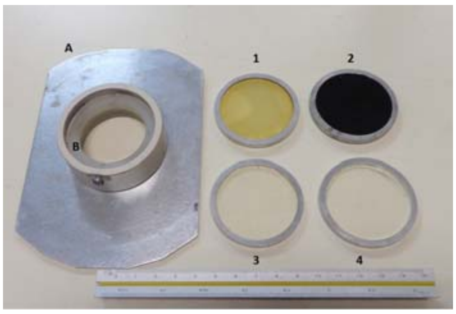

Figure 2: (A) Bottom view of the sample holder, (B) Docking site for the sample. Samples: (1) PVCP, (2) PVCP + 1% graphite, (3) Silicone and (4) Epoxy.

Samples 1 and 2 were prepared following the same protocol, the only difference was the mixture of graphite powder to the liquid PVCP before the procedure which consists of the steps: 1) Submitting the liquid PVCP to vacuum for around 30 minutes to extract air bubbles; 2) heating the liquid PVCP in a pan till reaching the temperature of 175 ^{0}C (approximately 40 minutes); 3) carefully casting it in a mold to avoid bubble formation; 4) Waiting the sample cooling down to ambient temperature.

The Silicone sample preparation consisted in: 1) mixing RTV 615A with RTV 615B in liquid form (mass proportion of 10 to 1); 2) Submitting the mixture to vacuum for around 30 minutes to extract air bubbles; 3) Carefully casting this mixture in a mold to avoid bubble formation; 4) Wait 24 h for the silicone to set.

The Epoxy sample was prepared by 1) mixing the resin Araldite® GY 257 with the catalyzer Aradur® 2963 (Huntsman Chemical Brazil Ltda., São Paulo, SP, Brazil) on mass proportion of 100 to 48 in while in liquid form; 2) Submitting the mixture to vacuum for around 30 minutes to extract air bubbles; 3) Casting this mixture in a mold carefully to avoid bubble formation; 4) Wait 24 h for the Epoxy to set.

A sample holder was put on top of the water recipient where the conic reflection target is immersed, it consist of a plate with a circular hole, which permits an undisturbed flow of ultrasonic energy when there is no target.

Measuring of ultrasonic power – The following equipment were used to measure ultrasonic power: RFB UPM-DT-1AV (Ohmic Instruments Company, Easton, MD, USA), ± 2 milliwatts resolution, and therapeutic ultrasound AVATAR TUS0203 III (KLD Electronic Equipment Biosystems Ltda., Amparo, SP, Brazil), 3.33 cm² ERA (effective radiation area), digital thermometer Fluke 52 (Fluke Corporation, Everett, WA, USA) and four samples.

The RFB is composed of an aluminum reflector cone and an absorber material tank that was filled with degassed water (boil distilled water for 20 minutes). The transducer, the cone and the samples were put in contact with water (in order to stabilize the system) for 1 hour before starting the experiments. All experiment was carried out in a closed ambient to prevent air flow additionally the experimental apparatus was placed on a fixed table to prevent vibration (Figure 3). The water temperature was maintained at 24 ± 3 °C for the appropriate functioning of the RFB.

Figure 3: Experimental setup. (A) Digital thermometer, (B) Radiation Force Balance, (C) Therapeutic ultrasound equipment.

For each sample the measurement followed the same procedure: a) recording the US power without the sample to work as a reference data; b) recording the US power with the sample in place. The power output adjusted to 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10W. The US equipment was set in continuous mode with 60 seconds transmission time, excitation frequency of 1 MHz. The experiments were repeated 15 times for each power.

Estimation of the insertion loss with the RFB data – The insertion loss was obtained by Equation 1 in which ultrasonic power is measured without the sample (P_0) (reference voltage), and with the sample ($P(x)$). Power is given in Watts and the sample thickness (x) given in centimeters. The insertion loss (α_{IL}) is given in dB.cm^{-1}.

$$\alpha_{IL} = 10\frac{\log\left(\frac{P(x)}{P_0}\right)}{x} \qquad (1)$$

Estimation of attenuation coefficient with the transmission - reception method – In the transmission-reception (TR) technique the experimental setup consisted of two transducers a transmitter (Tx) and a receiver (Rx) aligned in opposition according to their longitudinal axis X. The gap between transducer faces was large enough to insert the samples and perpendicular to the X axis. To keep transducers and sample in place an aluminum rail was employed. Transducers, rail and sample were immersed in water. Tx was driven by a Single Channel Arbitrary Function Generator Tektronix AFG3021 B (250 MS/s 25MHz). Tr was connected to an Oscilloscope Tektronix TDS420 150 MHz bandwidth (Tektronix, Inc., Beaverton, OR, USA) (Figure 4).

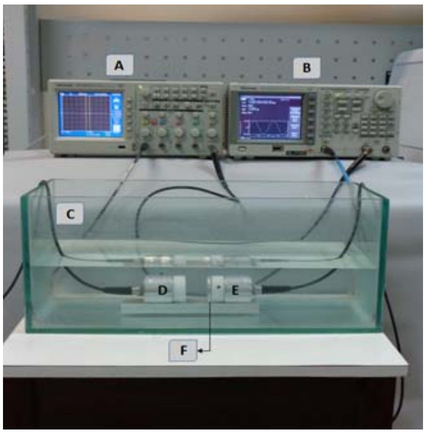

Figure 4: Experimental setup TR. (A) Oscilloscope, (B) Signal generating, (C) Acoustic tank, (D) Receive transducer, (E) Transmitter transducer, (F) Sample.

The measurement of the samples attenuation followed the same procedure: a) measuring the amplitude of the signal generated by Tx and detected at Rx with and without the sample inserted (A and A_o). The sample attenuation coefficient (α_S) is calculated according to equation (2) [13], here with adjustments to the intensity and dB.cm^{-1}, where A_0 represents the amplitude of the reference signal, A the signal amplitude with the sample and x the sample thickness. The attenuation coefficient of water (α_W) was assumed to be 2.5 x 10^{-4} [14].

$$\alpha_S = 2\alpha_W - \frac{1}{x}\left[2\ln\left(\frac{A}{A_0}\right) - 2\ln(1-R)\right] \times 4.34 \qquad (2)$$

Statistical analysis - The Kruskal-Wallis test was performed to verify the level of significance of the insertion loss variation regarding the power used in the experiment RFB method. Furthermore, the Kruskal-Wallis test was used to verify the hypothesis of statistical difference in insertion loss (RFB method) and attenuation coefficient values (TR method). When found significant differences the Tukey post-test was applied. Statistical tests were performed in SigmaStat 3.5 software (Systat Software Inc., San Jose, CA, USA). We assumed a value of $p < 0.05$ and confidence interval of 95 %.

Results

No significant difference was observed between the insertion loss values obtained with RFB for powers ranging from 0.5 to 10 Watts. For samples of PVCP (H = 9.764, p = 0.461) and Silicone (p = 0.972, H = 3.337), but differences were found for samples PVCP + 1% graphite (p <0.001, H = 29.830) and Epoxy (p <0.001, H = 75.027). Figure 5 represents the distribution of attenuation coefficient values obtained in eleven different power values. For each power adjusted in ultrasound, a group of fifteen insertion loss was calculated. These groups were compared each other. Table 2 shows the groups de IL for the power values that presented significant differences (Tukey Test).

Table 2: Power values with significant differences in the insertion loss

PVCP + graphite		Epoxy	
Power 1	Power 2	Power 1	Power 2
4	9, 10	0.5	6, 7, 8, 9, 10
		1	7, 8, 9, 10
7	9, 10	2	7, 8, 9, 10
		3	8

Power: Watts (W)

The fifteen values of α obtained by the TR method were compared to the group of fifteen α values obtained by the BRF for each power value. No significant difference was observed between the methods for samples of PVCP (p = 0.439, H= 11.048) and Silicone (p = 0.777, H = 7.273). However, differences were found for sample of PVCP + 1% graphite (p <0.001, H = 38,473) in TR method for power 4 and 7 W compared to method RFB. For Epoxy (p <0.001, H = 104,105) only the for powers 0.5, 1 and 2W such differences were shown.

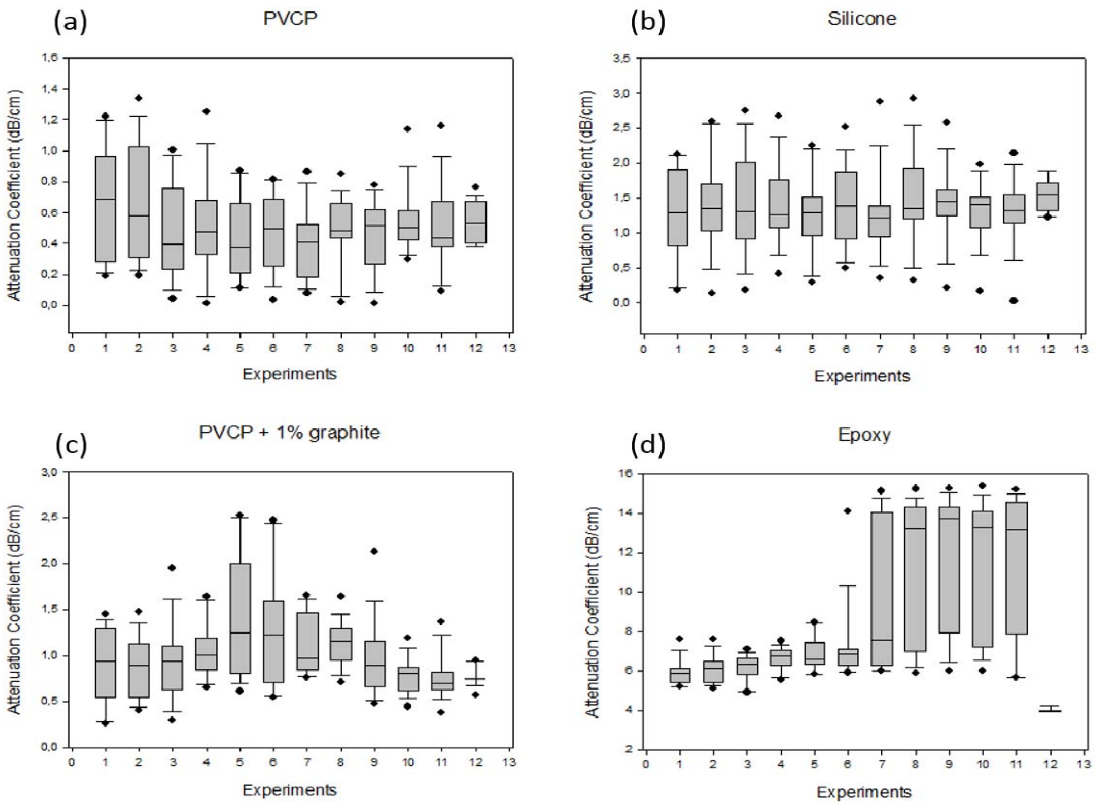

Figure 5: Attenuation coefficient obtained at 11 different power values (first 11 boxes). Box number 12 refers to the TR Experiment. (a) PVCP, (b) Silicone, (c) PVCP + 1% graphite and (d) Epoxy.

Discussion

The Epoxy sample showed an increase attenuation coefficient as power grows. Probably this occurred because it has higher absorption coefficient than other samples. Thus the samples heats at high intensities. According to [15] the absorption coefficient is independent of intensity. This non dependence was verified for high intensities only in the case of short irradiation time [16].

It was observed that the insertion loss value as a function of power depends on the material tested. PVCP samples with 1% graphite and epoxy showed statistically significant differences suggesting a non linearity. For PVCP and Silicone samples, the insertion loss is not dependent on power. These findings can be related to theories of non-linear elastic properties [17] and the effects of finite amplitude [18]. Depending on the intensity and irradiation time the US, absorption material can be large enough to alter the material properties and the relaxation time is not enough to compensate for this change. Not all groups showed correlation between the values of insertion loss and attenuation coefficient estimated by RFB and TR methods. This does not imply that the RFB is wrong but suggests that the dependence of attenuation on power as well as other phenomena related with propagation of ultrasound must be studied more carefully.

In these preliminary results for PVCP and Silicone, RFB method showed agreement with the TR method for all cases. For PVCP with graphite, the RFB and TR methods presented disagreement only for 4 and 7 W. For the Epoxy only in 0.5, 1 and 2 W agreement was observed.

Summarizing: The dependence of attenuation on temperature can explain part of the results. This agrees with the literature [15]. One relevant contribution of the present work is proposing a method enabling the investigation of ultrasound absorption in continuous regimen and high intensity in cases the sample material is modified by the irradiation. The behavior of the attenuation coefficient at high power is relevant for high-intensity focused ultrasound (HIFU). Tissues with high attenuation coefficients must be studied under this perspective in the case of physiotherapy.

In the current study, during the experiments, the water temperature was monitored and the power value was recorded when stabilized in RFB, but it would be interesting for future research dynamic assessment of the entire period for issuing the US, monitoring and recording the temperature of the sample and power values. The irradiation time of the US can be reduced if there is need to avoid heating the sample and also to prevent the formation of bubbles in the water in case of prolonged performing experiments, although this is not recommended by manufacturers of the scale.

In this work, the results of the insertion loss values obtained by the proposed RFB method in some cases approached of the values of attenuation coefficient obtained in the TR method. The differences may be due not only to transducers, different modes of emission and powers in each method, but also because corrections have to be made regarding the role of reflection, absorption and scattering for the two methods. The intended objective is to see how the RBF method can be used to estimate attenuation for high intensities.

Acknowledgements

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