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Frequency and concentration dependence of the ultrasonic backscatter coefficient in a soft tissue mimicking material

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In medical ultrasound, the backscatter coefficient is used to quantify the scattering properties of biological tissues. It is defined as the differential scattering cross section per unit volume for a scattering angle of 180°. In this study, measurements of backscatter coefficient are made on Tissue Mimicking Materials (TMM). These are materials the acoustic properties of which (velocity, attenuation, scattering) are close to those of biological tissues. Measurements of this coefficient have been achieved on a mixture of gelatin and distilled water containing microscopic graphite particles with a mean radius of 18 micrometers which were randomly distributed. Samples concentrations ranged from 50 to 200 g of graphite per liter of gelatin. The backscatter coefficient was evaluated using both Sigelman and Reid method and Chen method in a frequency range around 5 MHz. The evolution of this coefficient as a function of frequency and scatterers's concentration will be presented. Comparison of experimental values with those obtained from Faran's theory permits the estimation of the number density of graphite particles in the TMM.

1 Introduction

In medical acoustics, the backscattering coefficient is commonly used to quantify the scattering properties of ultrasound by biological tissues. It is defined as the differential scattering cross section per unit volume at a scattering angle of 180° [1]. It is recently become a very important way for the characterization of various tissues such as blood, heart, liver, prostate, breast and bone [3, 2, 4]. Several authors have attempted to develop the most reliable methods for the determination of this coefficient [5, 6, 7, 8, 9, 10]. These have been applied to a large extent [11, 12, 13, 14, 15, 16]. The standardization of the measurement of this coefficient is however still relevant [2].

Generally, measurements of acoustic parameters such as velocity, attenuation and scattering coefficient are made on phantoms of biological tissues [17, 18, 19, 20]. Ideally, such materials should be capable of mimicking humain tissues with respect to these characteristics. The speed of sound in the tissue mimicking material (TMM) should vary in the range from approximately 1460 m/s, which is characteristic of human fat tissue, to 1640 m/s for the human eye's lens. The attenuation coefficient with respect to frequency of the material should range from approximately 0.4 dB/cm/MHz,which is characteristic of human fat tissue, to 2.0 dB/cm/MHz for the human muscle tissue. Aditionally, the attenuation coefficient should be approximately proprtional to the ultrasonic frequency [21].

Measurement of the backscattering coefficient will be made by using the method of Sigelman and Reid and that of Chen. The results obtained by both methods will be compared with the theoretical curve obtained by Faran's model [22]. Then, the adjustment of this curve with the experimental results permits the estimation of the concentration of graphite in the TMM.

2 Theory

2.1 Sigelman and Reid Method (1973)

Sigelman and Reid are the first who have developed a method to measure the backscattering coefficient η of a volume containing a random distribution of scatterers [5]. This is a substitution method in which the rms value of the gated backscattered signal is compared to the rms value of the reflected signal on a reflector positioned at the same distance as that separating the transducer and the scattering volume. The ratio of these two quantities gives the backscattering coefficient. The sample is insonified by a sine-wave burst from a narrow-band planar transducer. The actual volume of the beam (ie the volume of scatterers who contribute significantly to the backscattered signal) is determined laterally by the -3 dB width of the ultrasonic beam and axially by a time window. In this approximation, the field is assumed to be constant everywhere inside the cylindrical volume so determined.

The expression of the backscattering coefficient is given by:

$$\eta = \frac{P_s}{P_i}\frac{R^2K^2}{V_s\Gamma^4 A(f)}, \qquad (1)$$

where P_s is the mean backscattered acoustic power and P_i the incident one. $Vs = S\frac{c(t_2-t_1)}{2}$ represents the scattering volume and $A(f) = \left(\frac{e^{\tau c\alpha}-e^{-\tau c\alpha}}{2c\alpha\tau}\right)\left(\frac{e^{-2\alpha c t_1}-e^{-2\alpha c t_2}}{2c\alpha\Delta t}\right)$ the attenuation correction function for the sample. S is the lateral section of the scattering volume and $\Delta t = t_2 - t_1$ the temporel gate duration. Γ is the acoustic pressure transmission coefficient between the sample and the surrounding medium which is, in this case, water. K is the pressure reflection coefficient at the sample- water interface. τ is the pulse duration. R is the distance from the transducer to the scatternig volume center. α is the attenuation coefficient and c the ultrasonic propagation velocity in the sample.

2.2 Chen and *al* method (1997)

A new formualtion for data reduction of the backscattering coefficient was given by Chen and *al* [10]. This formulation has no restrictions on the positions of the scattering volume and of the reflector plane relatively to the transducer. The diffraction function of the transducer is strictly calculated then approximated in the case of a planar transducer and a focusing transducer. Moreover, the method of Sigelman and Reid can be derived from this formulation in the case of a planar transducer.

The model developed by Chen allowed us to deduce an expression of the backscattering coefficient. By placing the reference plane at one- half the transducer- scattering volume center distance: $z_{ref} = \frac{R}{2}$, it becomes:

$$\eta(\omega) \cong \frac{\left\langle |V_s(r \in V;\omega)|^2 \right\rangle}{\left|\overline{V}_{ref}(z_{ref};\omega)\right|^2} \frac{K^2 (ka)^2 (R/r_0)^2}{\Gamma^2(\omega) A(R;\omega) 4\pi^3 . l . E_\infty} \times \exp\left[-(2/\pi)(R/2r_0)^{1/2}\right] \exp\left[-E_\infty \pi (R/r_0)^2\right], \quad (2)$$

where $\left\langle |V_s(r \in V;\omega)|^2 \right\rangle$ is the mean spectrum amplitude of the backscattered signals and $\left|\overline{V}_{ref}(z_{ref};\omega)\right|^2$ the spectrum amplitude of the signal reflected on the reference plane. $E_\infty = 0.46$, R is the distance transducer- scattering volume center. $r_0 = ka^2/2\pi$, with k the wave vector and a the transducer radius. $l = c\Delta t/2$ is the scattering volume length. Δt being the gate duration. $A(R;\omega)$ is the attenuation correction function . In the case that attenuation in the surrounding fluid is negligible, it becomes:

$$A(r \in V;\omega) \cong \exp\left[-4\alpha(R - r_i)\right] \times \frac{\exp\left[2\alpha l\right] - \exp\left[-2\alpha l\right]}{4\alpha l} \times \frac{\exp\left[2\alpha \Delta t c\right] - \exp\left[-2\alpha \Delta t c\right]}{4\alpha \Delta t c}, \quad (3)$$

where r_i is the distance between the transducteur face and the front face of the sample.

3 Experimental study

3.1 Phantoms elaboration

The biological phantoms were madeof a mixture of distilled water and gelatin powder with a mass concentration of 10%. This concentration was the same for all samples. Distilled water was heated slightly below the boiling temperature. Then, the gelatin powder (VWR) was added to water. An electric mixer was used to homogenize the mixture.

The graphite powder (Aldrich, molecular weight 12.01 g/mol, density 1.9 g/cm^3, mean radius 18 μm) was poured into the homogenous mixture. The gel obtained was then poured into two metal molds of cylindrical shape, with the same diameter and height 50 mm. The internal volumes containing the gel were 80 ml and 60 ml respectively. The gelation of the samples has been accelerated by plunging them into water at 4° C, in order to prevent the settling of the graphite powder. TMM fast gelation methods that give better results, such as those using nitrogen could be considered [26].The samples were then placed in the refrigerator for at least 10 hours.

Graphite powder acts as ultrasonic scatterer in our case. To demonstrate the effect of the number of scatterers and therefore their concentration on the backscattering coefficient, six sample pairs were elabored at different concentrations: 50 g/l, 75 g/l, 100 g/l, 150 g/l and 200 g/l.

3.2 Experimental setup

Figure 1 shows the experimental apparatus. It is composed from a tank filled with distilled water. A reflector plate placed at its bottom supports the metallic mould of cylindrical shape containing a gelatin gel. The latter is covered by a cellophane film acting as Saran window. An immersion piezoelectric, planar, circular transducer (Panametrics) of 19 mm diameter and 5 MHz nominal frequency, is fixed on a metallic holder of cylindrical form. This device provides, at the frequencies concerned, a good parallelism between the face of the transducer and that of the sample. The transducer is connected to a transmit-receive generator (Sofranel 5072PR) delivering negative pulses of large amplitude and short duration. The received signal is visualized on a digital oscilloscope (Tektronix TDS 2012). The digitized signal is transferred to a microcomputer via a GPIB bus. The acquired signal is then processed by using a Matlab program.

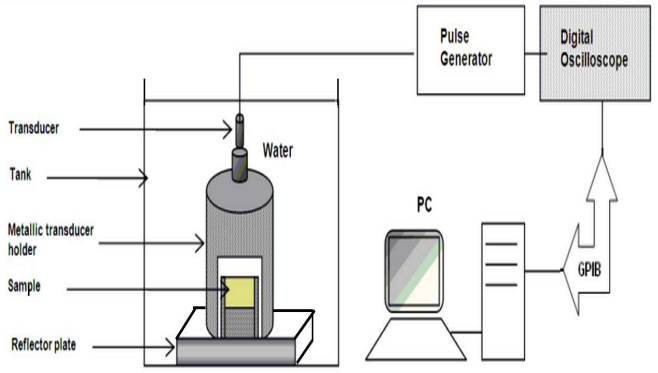

Figure 1: Experimental setup

3.3 Propagation velocity and attenuation coefficient measurements

The method used in our work is that developed by Peters and Petit [23]. It is an impulse method which allows a processing of the signals on a broad frequency range. It also permits the determination of the phase shift, the attenuation and the phase velocity [24, 25].

Two aluminum moulds containing two samples of gelatin gel of $e_1 = 3$ cm and $e_2 = 4$ cm heights respectively, were used. The incident pulsed ultrasonic wave propagates in the distilled water before penetrating the cellophane layers then the gelatin gel to the back faces of the moulds. Those are located at distances z_1 and z_2 from the transducer face, respectively. This provides two echoes emanating from two different distances.

Measurement of propagation velocity of ultrasound is based on the measurement of the time of flight (TOF) difference of the ultrasonic wave in the two samples. This measurement can be obtained either by a direct reading on the oscilloscope screen or by signal processing techniques such as Hilbert transform or cross-correlation function. This last method was selected in this work. The propagation velocity is then given by:

$$V_g = \frac{2\Delta z}{\varsigma}, \quad (4)$$

where Δz represents the distance difference traveled by the ultrasonic wave, ς the corresponding time of flight .

3.4 Backscatter coefficient measurements

3.4.1 Measurement procedure

In order to get the reference signal, a planar reflector of duralumin is placed at one- half the transducer - scattering volume center distance. This is equivalent to a measurement of the response of an identical receiving transducer positioned at the center of thescattering volume (the distance traveled by the pulse echo is $2\times(R/2) = R$).

The determination of the backscattering coefficient requires an adequate processing of the backscattered signals: amplification, temporal gating, frequency averaging. An amplification gain of 20 dB was applied to the recieved signal. We used a Tukey window (h = 0.25) with 10 μs duration. In addition, to correct the interface effects, the transmission coefficient at the water - sample interface and the reflection coeffcient at the water -duralumin plate interface are taken into account.

For each measurement of the backscattering coefficient, 10 backscattered signals acquisitions corresponding to different parts of the sample were performed. An average value over the ten corresponding spectra was calculated in order to reduce noise and to obtain a smoother spectrum.

3.5 Results and discussion

3.5.1 Evolution of the backscatter coefficient versus frequency and graphite concentration

Backscatter coefficient (BSC) variations obtained by using the Sigelman et Reid method and the Chen method for different graphite concentrations with a transducer of 5 MHz nominal frequency, have been represented on figure 2.

These curves show that the backscatter coefficient increases with graphite concentration in the TMM. This is expected in view that an increasing of the scatterers number involves increasing the acoustical energy losses caused by scattering. It is also noted a discrepancy between the values of the BSC obtained by the Chen method and the Sigelman and Reid method. Generally the curves show the same increasing rate for different concentrations of graphite except for the concentration of 100 g/l. This could be due to manufacturing conditions for each graphite concentration in the TMM. Other parameters that can influence the final structure of TMM such as variations in the ambient laboratory temperature in the development of TMM and experimental measurements have to be considered.

3.5.2 Comparaison with Faran's theory

Faran's theory predicts scattering by a single elastic sphere immersed in a non viscous fluid [22]. Several studies have tested the efficiency of this theory in predicting experimentally the backscattering coefficient of biological phantoms [1, 26, 11, 2, 12, 14, 16, 15]. Faran's theory permits the derivation of the differential scatternig cross section. Backscatter coefficient for a distribution of uncorrelated identical scatterers should have the same frequency dependence as the differential backscattering cross section of a single scatterer except for a factor equal to the number of scatterers per unit volume.

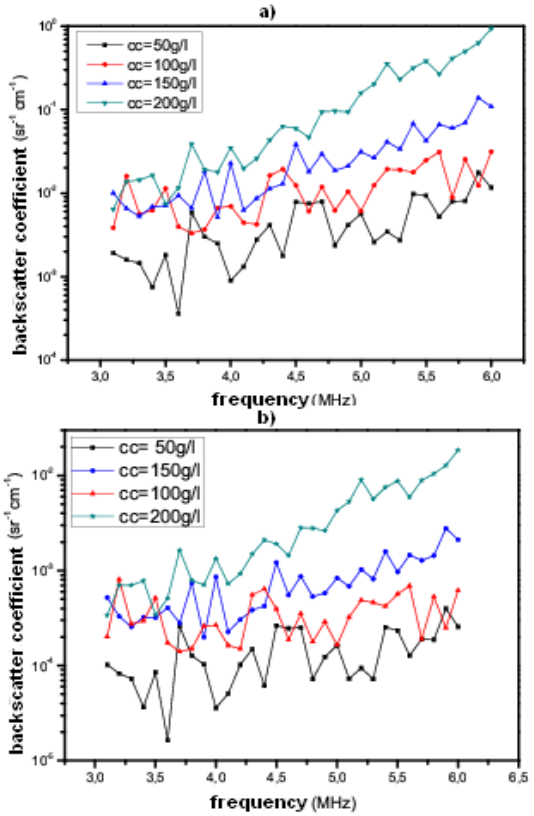

Figure 2: Experimental curves of the backscatter coefficient versus frequency around 5MHz for different graphite concentrations (50 g/l, 100 g/l, 150 g/l, 200g/l) obtained by using a) Sigelman and Reid method and b) Chen method.

The results presented above allow to achieve a quantitative comparison between the results predicted by the Faran's theory and those obtained experimentally. To do this, we adjust the values of the differential cross section of scattering for a single scatterer obtained by Faran's theory to the experimental curve of the backscattering coefficient by multiplying the values of the first curve by a factor, which is proportional to the number of scatterers per unit volume of the TMM [26].

Figure 3 shows the experimental curve obtained by the Chen method, their fit (dashed lines) and the theoretical curve of Faran (solid lines) after adjustment by this factor. We note that there is an acceptable agreement between the theoretical curves and the fits of the experimental data in the frequency range considered except for the concentration of 100 g/l. The scatterers concentration estimation by using this method is not very accurate because Faran's theory is based on numerous assumptions and approximations that are not entirely fulfilled. In our case, the graphite grains are not spherical as assumed in the theory. Moreover, the actual number of grains per unit volume and the actual distribution of the size of scatterers are not known. Moreover, in this theory, the coherent scattering and multiple scattering are neglected even though they may occur. Given all these indications, it can be considered that the results presented show an acceptable agreement

with the Faran's theory.

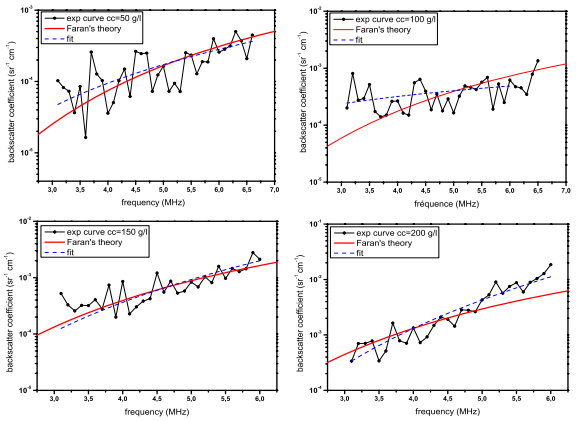

Figure 3: Curves giving the frequency dependence of the backscatter coefficient obtained from Chen method in TMM for different graphite concentrations (50g/l, 100g/l, 150g/l, 200g/l), their fit and Faran's curves.

3.5.3 Scatterers concentrations estimates

Table 1 gives the estimated values of the concentration of scatterers per cm^3. They were obtained using the methods mentioned in the previous paragraph.

Note that the estimated valuesof the number of scatterers per unit volume are larger in the case of the Sigelman and Reid method. This is predictable given that the BSC curves obtained by this method show greater values than those obtained by the Chen method. It is also noteworthy that the increase of the concentration valuesobtained by the Chen method are more regular than those obtained by the Sigelman and Reid method. Knowledge of the actual number of scatterers per unit volume could help us determine which of the two methods gives the most accurate results.

Table 1: Graphite concentration per unit volume estimates obtained by Sigelman et Reid method and Chen method.

concentrations (g/l)	Estimated	concentration (cm^{-3})
	Sig and Reid	Chen
50	3×10^5	8.5×10^3
100	7×10^7	2×10^4
150	1.5×10^6	4.5×10^4
200	6×10^6	1.5×10^5

4 Conclusion

The experimental curves of the backscatter coefficient show a fairly good agreement with Faran's theory, except for some cases. This encourages us to improve the experimental measurement conditions. The adjustment of the experimental curves to those obtained from Faran's theory allowed us to estimate the number of scatterers per unit volume. This estimate would have been better evaluated if we knew in advance the volume concentrations in order to calibrate the method. A better understanding of the characteristics scatterers permits to improve our results.

It can also be concluded that the addition of graphite or other components allow adjusting the acoustic properties of the TMM according to the biological tissue we want to imitate. In our case, we were able to approach the acoustic properties of soft biological tissues.

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