Measurement system for experimental determination of acoustic properties of gels at INRIM

C Musacchio, G Durando, A Bernardi and A Troia

INRIM - Istituto Nazionale di Ricerca Metrologica-, Strada delle Cacce 91, 10135 – Torino, Italy

E-mail: c.musacchio@inrim.it

Abstract. Due to the large diffusion of ultrasonic technique in medicine, use of tissue mimicking materials to understand physical interaction of ultrasound has grown in importance. From this view measuring acoustic properties of such materials is crucial. This work shows the settlement at INRIM laboratory of a simple system for acoustic properties measurements with particular interest in attenuation of ultrasound. The system is based on substitution method and Fourier analysis and allow the evaluation of speed of sound, impedance and attenuation in the frequency range between 3 MHz and 12 MHz.

1. Introduction

The characterization of ultrasonic fields generated in water by transducers as provided by national and international standards is surely a fundamental tool for the control of device performance and for patient safety protection, but the information they give is not complete. As a matter of fact, they describe the morphology and intensity of the field, but not the effect induced by this field in real tissue.

A new approach is required, based on simulation of physical effects and the quantitative measure of them through in vitro measurements. So, the issue is to realize new materials for simulation of acoustic properties of real tissue, new parameters which really refer to biophysical effects intensity, and a robust methodology for measuring them. At the moment a really great interest is present in international scientific community and in standardization board towards research in this field [1-8].

The first problem for this approach would be the realization of suitable tissue mimicking phantoms. They are object made with materials whose physical properties are as close as possible to those of real tissues. [9]

Some object of this kind already exists and have been realized for the control of performance of medical ultrasonic devices. As an example they exist for sale phantoms for the control of image quality for scanners. They are phantoms, usually made of agar gel or other kind of gels. Materials similar to tissue mimicking object However, for the realization to be studied in detail: the realization of new measurement method.

This work describe a study of tissue mimicking materials and the realization of a quite simple set-up and a easy method for testing these materials and in particular for the determination of their main acoustic properties, i.e. speed of sound, acoustic impedance and absorption coefficient [10].

The measurement system designed and the activity conducted can be considered a good and promising starting point for further studies.
2. Materials and methods

Acoustic impedance and attenuation coefficient of a tissue mimicking gel have been measured using a substitution method and a trough transmission technique. In the developed system the unknown acoustic properties of a gel sample are obtained from the comparison with the properties of water. In extreme synthesis the method requires two ultrasonic transducers, one for the generation of a wave pulse and the other for the detection of the wave after its propagation through the sample. Substituting the unknown sample with water allows to estimate its acoustic properties by comparing the received signal when the sample is inserted in the propagation path and when the wave travels only through water.

The samples used for the measurement system testing are polyacrylamide gels. They have been realized in our laboratory starting from information found in scientific literature [10]. The recipes and production system has been improved in order to realize gels with different acoustic characteristics.

2.1. Measurement setup

The measurement setup is quite simple and it is composed of two wide band ultrasonic transducers, one used as a transmitter and the other as a receiver, a signal generator, to drive the transmitter, and a digital oscilloscope for acquire both the electrical signal sent at the transmitter input and the electrical signal produced by the receiver. All the instruments are remote controlled with a personal computer. The software for the instrument control, the signal generation and acquisition has been developed.

The signals acquired are then processed by an other home made software to calculate acoustic impedance and absorption coefficient of the sample. Figure 1 shows a picture of the measurement setup.

![Figure 1. Picture of the measurement box with the sample between the two transducers](image)

The measurement process involves a two steps procedure: first a measure with water, and then a second measure with the gel sample.

The two transducers are placed at both end of a little water tank, one in front of the other. A sinusoidal burst with a limited number of cycles at the working frequency of the transducer is generated. Driven by the generator, the transducer emits pulsed ultrasonic waves at the set pulse frequency. Emitted and received signals, are acquired by the digital oscilloscope and stored on pc. In order to reduce the noise of the signals each acquisition is the result of a large number of average and the acquisition is repeated about ten times so that the subsequent analysis is conducted over a larger number of signals.

![Figure 2. A schematic representation of the procedure of measurements. The acoustic properties of the sample are measured by a comparison with the known properties of water](image)
Because of the dependence of the acoustic properties of materials from their temperature the process has been designed so that its duration is quite short (about few minutes) so that environmental influence variables has not time enough to change significantly. However during the whole measurement the temperature of the water tank is monitored continuously with a thermocouple. When the measure is completed the gel sample is inserted in the water tank between the transmitter and the receiver and the described process is repeated (Figure 2).

2.2. Signal processing and data analysis

The signal processing and the data analysis is carried out off line by a software, developed in LabView 7.1. First of all software calculates the time of flight of the wave in water and in presence of the sample. The cross correlation of the two time functions (transmitted and received signals as acquired by the oscilloscope) is calculated and the time delay that maximizes such a function is taken as the flight time. So the speed of sound in the sample, $c_S$ can be calculated from the measured times of flight as:

$$c_S = \frac{c_{H2O} \cdot d}{d + (t_S - t_{H2O}) \cdot c_{H2O}} \quad (1)$$

where $c_{H2O}$ is the speed of sound in water, $d$ is the sample length, $t_{H2O}$ is the signal time of flight measured in water and $t_S$ is the time of flight in presence of the sample. $c_{H2O}$ is calculated from the water temperature according to existing theoretical models.

Once the sound speed in sample is known, its impedance $Z_S$ can be immediately obtained from the formula:

$$Z_S = \rho_S \cdot c_S \quad (2)$$

with $\rho_S$ being the measured sample density.

The reckoning of the absorption coefficient requires the comparison between the amplitude of the signal received when the whole path is water with the amplitude of the signal when the sample is present. The signal analysis is conducted in the frequency domain so that it is possible to estimate the absorption behaviour at different frequencies with a single calculation.

Without considering in detail all the phenomena occurring, it is possible to consider all the system as a black box which transform an electrical signal into an other. According to this simplified model, in the frequency domain, it is possible to express the component of the amplitude of the received signal at the frequency $f$, $A_{rw}(f)$, as:

$$A_{rw}(f) = A_{tw}(f) \cdot F_{tw}(f) \quad (3)$$

with $A_{tw}(f)$ being the Fourier transform of the received signal, $A_{tw}(f)$ is the Fourier transform of the generated signal, and $F_{tw}(f)$ is the transfer function of the system. The last term of the equation is certainly an abstraction, but it is possible to imagine that it contains the effect of many physical phenomena, such as the transduction efficiency of the transmitter and the receiver, the geometrical spreading of the ultrasonic wave, the diffraction effect, the absorption in water, usually considered negligible for so short distances, and so on.

In a similar way when the sample is inserted, the amplitude of the received signal can be expressed as:

$$A_{rs}(f) = A_{rs}(f) \cdot F_{rs}(f) \quad (4)$$

where $A_{rs}(f)$ is the Fourier transform of the received signal with the sample between the transmitter and the receiver, $A_{rs}(f)$ is the transform of the signal generated by the function generator and $F_{rs}(f)$ is the transfer function of the system.

In $F_{rs}(f)$ two very important effects are present that missed in the former term: a loss in amplitude due to the impedance de-coupling between the two different propagation media and the attenuation in gel. The amplitude of the transmitted wave, $A_T$, between two media is the result of the product between the amplitude of the incident wave, $A_I$, and the transmission coefficient, $T_{1,2}$, according to the equation:
\[ A_f = T_{1-2} A_f = \left( \frac{2Z_2}{Z_2 - Z_1} \right) \]

where \( Z_1 \) and \( Z_2 \) are the acoustic impedance of the two media.

Therefore, if we neglect all the effects but the loss due to de-coupling the relationship between the received signal with water only and with gel sample would be:

\[ A_{rs} = A_{rw}(f) \cdot T_{s-w} T_{w-s} = A_{rw}(f) \cdot \left( \frac{4Z_w Z_s}{(Z_w - Z_s)^2} \right). \]

The value of attenuation coefficient in water can be neglected and the only attenuation in gel can be taken in consideration. The attenuation coefficient of gel, \( \alpha \), is expressed in dB/cm.

If we now summarize all the consideration made about the main effects experienced by the wavelets travelling along the gel it is possible to suppose a relationship between the transfer functions which accounts for the effect of the impedance mismatch between water and gel sample as well as of the attenuation into the gel.

\[ F_{ss} = F_{rw} \cdot T_{s-w} \cdot T_{w-s} \cdot 10^{\frac{\alpha d}{20}} \]

Since the received signal can be influenced by an accidental variation of the electrical signal sent to the transmitted, in order to correct for this effect, it has been preferred to compare not directly the Fourier transform of the received signals, but the frequency response of the system, it is to say the frequency components of the received signals normalized for the frequency components of the corresponding input signal. Then attenuation coefficient is calculated as:

\[ \alpha(f) = \frac{20}{d} \log_{10} \left[ \frac{A_{rs}(f)}{A_{rw}(f)} \cdot \frac{4Z_w Z_s}{A_{rs}(f) \cdot (Z_w - Z_s)^2} \right]. \]

3. Measurement results

Gel samples used for the measurements have been realized according to the procedure assessed and their main acoustic parameters have been calculated. First test have been done with simple polyacrylamide gel. In figure 3 the results of a set of five measurements of the attenuation coefficient, conducted at INRIM laboratories over the same sample, are reported. From the data it is possible to recognise the dependence of the coefficient from the frequency. It can be seen as the data dispersion is quite limited in the frequency range 3-15 MHz, but they dramatically spread when the frequency increases, due to the low signal to noise ratio at the higher frequencies. So the attenuation coefficient has been evaluated for the frequency range between 3 MHz and 12 MHz.

Measurements have been done on gel samples obtained with different recipes. In particular polyacrylamide gels have been realize with kieselguhr mixed in the material during preparation process in order to obtain different attenuation coefficient.

Measurement results of attenuation coefficient are reported in figures 4 and 5. Results are compared to those made at NPL on similar samples produced at INRIM laboratory and sent to NPL for characterization. NPL results are marked as “reference values”.

Advanced Metrology for Ultrasound in Medicine (AMUM 2010) IOP Publishing
Journal of Physics: Conference Series 279 (2011) 012026 doi:10.1088/1742-6596/279/1/012026
Figure 3. Results of some preliminary measurements of attenuation coefficients in the frequency range 2.5–18 MHz. Measurements executed at the INRIM laboratories

Figure 4. Results measurements of attenuation coefficients in the frequency range 3 – 12 MHz. of sample with 1.5% weight fraction mixed.

Figure 5. Results measurements of attenuation coefficients in the frequency range 3 – 12 MHz. of sample with 3% weight fraction mixed.

Power law curve has been used to fit the data and to obtain the value of the attenuation coefficient as a frequency function. The two samples under investigation differ only for the weight fraction of
kieselghur that is 1.5% in the first case and 3% in the second. The attenuation coefficient found are respectively 0.12 dB/cm/MHz and 0.21 dB/cm/MHz.

4. Conclusion and future development

The present set up allows measurement of attenuation coefficient in a frequency range from 3 MHz to 12 MHz. INRIM data and reference data are quite in a good agreement, especially for lower frequencies (below 6 MHz), while at higher frequencies the two data sets tend to diverge with systematically higher values for the NPL data. The difference is significant in particular for the less attenuating sample. This discrepancy could be explained considering that the two samples analysed in the two different laboratories can present some differences due to their maintenance, but a complete explanation of possible causes of discrepancy should be needed. Anyway the measurements can be considered reliable considering the uncertainty of the INRIM values that is about 10%.

The measurement system can be used for simple, easy and quick measurement of characterization of gel samples.

The method described has shown to be promising, but surely need some further development. One problem is the too low signal to noise ratio for measurements relative to absorption coefficient in the spectral band far from the acoustic working frequency of the transducer. The problem could be solved by using other kind of transducers, at the moment not present in the laboratory, with a broader band or using a set of transducers with different acoustic working frequency able to cover a wider range.

The frequency range under investigation is of interest in medical application. One of the future targets will be to succeed in characterizing the acoustic properties of the gels in used for simulating physical effects induced by High Intensity Focused Ultrasound fields.

The system realized for acoustic characterization of material will be useful for the aim of studying heating effects on tissue mimicking phantom induced by High Intensity Focused Ultrasound fields.

5. References

[1] Shanna Lochhead et al “A gel phantom for the calibration therapy” 2004 IEEE Ultrasonics Symposium 1481-1483
[2] Burlew MM, Madsen EL, Zagzebski JA, Banjavic RA, Sum SW. A new ultrasound tissue-equivalent material. Radiology 1980;134: 517–520.
[3] Lafon C, Vaezy S, Noble M, et al. New synthetic tissue-mimicking phantom for high intensity focused ultrasound. Proceedings of the International Congress of Acoustic, Rome, Italy, 2001.
[4] Wu J. Tofu as a tissue-mimicking material. Ultrasound Med Biol 2001;27:1297–1300. 1422 Ultrasound in Medicine and Biology Volume 30, Number 10, 2004
[5] E.L. Madsen et al. “Tissue-Mimicking Oil-in-Gelatin Dispersions for Use in Heterogeneous Elastography Phantoms” Ultrasonic Imaging 25, 17-38 (2003)
[6] A. F. Prokop et al. “Polyacrylamide gel as an acoustic coupling medium for focused ultrasound therapy” Ultrasound in medicine and biology, volume 29 number 9, 1351–1358 (2003)
[7] Kondo, T.; Kitatuji, M.; Kanda, H. “New tissue mimicking materials for ultrasound phantoms” Ultrasics Symposium, (2005) IEEE; 3 (18-21), 1664 – 1667
[8] J.J. Ammann, G. Donoso , et al. “Tissue-mimicking materials assessment through ultrasound velocity measurement” Medical Imaging 2003: Ultrasonic Imaging and Signal Processing. Edited by Walker, William F.; Insana, Michael F. Proceedings of the SPIE, Volume 5035, pp. 440-451 (2003).
[9] F.A. Duck, “Physical properties of tissue. A comprehensive reference book”, New York: Academic Press, 1990.
[10] El. Madsen et al “ Interlaboratory comparison of ultrasonic backscatter attenuation and sound speed measurements” J. Ultrasound Medicine, vol. 18 615-631 (1999).

Acknowledgements

This work was supported by the European Community's Seventh Framework Programme, ERA-NET Plus, under Grant Agreement No. 217257 (EURAMET joint research project).