The importance of expression of uncertainty of acoustical parameters of ultrasonic phantoms

L E Maggi1,2,3, A B B Souza1, R M Ichinose1, W C A Pereira1, M A von Kruger1, R P B Costa-Felix3

1 Programa de Engenharia Biomédica / COPPE – UFRJ, Rio de Janeiro, Brasil.
2 Departamento de Fisioterapia / Universidade Estadual de Goiás, Goiânia, Brasil.
3 Ultrasound Laboratory, Diavi/Dimci/Inmetro, Duque de Caxias, RJ, Brasil.

1luis.maggi@gmail.com

Abstract. The measurement of uncertainties in scientific experiments improves greatly quality and reliability of the results. However, in many cases, experimental results are only expressed by its average value and standard deviation. The longitudinal velocity and attenuation coefficient are acoustic parameters commonly used to characterize biological tissues and materials. In this work it is studied the uncertainty in experiments designed to evaluate these parameters on two different materials (silicone rubber and PVCP). The uncertainties were studied following the Guide to the Expression of Uncertainty in Measurement and calculated by a program in Labview8.6. One setup was developed to measure the acoustic parameters by a transmission/reception technique. Five signals of each medium (water and materials) were collected. The attenuation coefficient was calculated using the relation between the amplitude spectrum peak of the water signal and its respective point on the spectrum of the material signal. The longitudinal velocity was calculated using the time delay between signal peaks (from water and from the material). The individual uncertainties of each part of setup were estimated and these values permitted to identify which were the sources of uncertainty that most contributed to increase the value of associated uncertainty. It permitted to improve experiment’s quality and reliability.

1. Introduction

Ultrasonic Phantoms are materials intended to mimic acoustic properties of biological tissue (propagation velocity, attenuation coefficient and acoustic impedance [1,2,3] and are used to calibrate and evaluate the quality of ultrasound equipment among other applications. To develop these phantoms it is necessary to measure the acoustic properties of their constituents. The Laboratory of Ultrasound (LUS) of the Biomedical Engineering Program (PEB) from the Federal University of Rio de Janeiro (UFRJ) and the Ultrasound Laboratory from Diavi/Dimci/Inmetro are implementing a methodology for measuring the attenuation coefficient and longitudinal velocity of the testing objects along with their uncertainties expression.

Several published studies such as Prokop et al. (2003) [1], Takegami et al. (2004) [2] and Zell et al.
(2007) [3] present the attenuation coefficient and acoustic velocity just as mean values and standard deviations. The measurement of uncertainties in scientific experiments greatly improves quality and reliability of the results. Publications such as the Guide to the Expression of Uncertainty in Measurement (GUM) by ISO (Adopted by INMETRO [4]) provide a methodology to calculate the uncertainty.

The aim of this work was to apply the method described in GUM to express the uncertainties of measurement of attenuation coefficient, obtained by the method implemented in LUS.

2. Materials and Methods

2.1. Materials

Two different materials were used as testing objects: RTV615 silicone rubber (GE) and PVCP (M-F Manufacturing Co). The RTV615 is a silicone product, consisting of a solution of two viscous components (RTV 615 A: RTV 615 B) when mixed in a 10:1 proportion, they initiate a healing process, even at room temperature. To prepare a PVCP phantom, the liquid is placed in a beaker and then put into a vacuum chamber to remove air bubbles. The healing of both phantoms were made in containers with 2.20 x 3.05 x 4.68 cm.

2.2. Measurements

The experiment to measure ultrasound attenuation coefficient and velocity in phantoms is divided in two stages. In the first stage, the phantom is positioned between two similar transducers, such that one of these emits a pulse signal (15 cycles and voltage of ± 10 Vpp) and the other receives the signal transmitted through the phantom (Figure 1). In the second stage, the phantom is removed and the signal measurements are made in a water layer with same phantom thickness. The measurements performed in water are used as reference.

![Figure 1. Design of experimental setup.](image)

The functions representing the measurement of attenuation can be seen in equation (1), $\alpha$ is the phantom attenuation coefficient, $V_{\text{pha}}$ and $V_{\text{ref}}$ represent the amplitudes of ultrasound signal in phantom and in water respectively. Two different amplitudes were used to compare (in spectral - FFT and time...
- RMS domains) using a program developed in Labview 8.6 (AcousticTrans6 in Figure 2). D is the phantom thickness. Nonlinear propagation effects (not investigated in this study) were assumed to be negligible for the \( \alpha \) measurement because pressure amplitudes were small and propagation paths were short.

\[
\alpha = \frac{20 \log \frac{V_{\text{pha}}}{V_{\text{ref}}}}{D}
\]

In equation (2), \( v_{\text{ref}} \) represents the ultrasound velocity in water according to equation (3), where \( T \) is water temperature [5]. \( t_{\text{ref}} \) and \( t_{\text{pha}} \) are respectively the time of flight (TOF) of the ultrasound signal into the water layer and into the phantom.

\[
v_{\text{pha}} = v_{\text{ref}} \frac{t_{\text{ref}}}{t_{\text{pha}}}
\]

\[
v_{\text{ref}} = 1.40238744 \times 10^3 + 5.03836171 T - 5.81172916 \times 10^{-2} T^2 + 3.34638117 \times 10^{-4} T^3
\]

\[-1.48259672 \times 10^{-6} T^4 + 3.16585020 \times 10^{-9} T^5
\]

Uncertainty types A and B of each source that contributes to the expression of attenuation uncertainty were calculated and applied in equation (4), where \( x \) could be either thickness (D) or amplitudes of ultrasound signal in phantom (\( V_{\text{pha}} \)) or in water (\( V_{\text{ref}} \)), according to ISO GUM 2003[4].

\[
u^2(x) = u_A^2(x) + u_B^2(x)
\]
2.3. Combined standard uncertainty

It is the quadratic sum of the product of each uncertainty component with their respective sensitivity coefficient. This coefficient is defined as the partial derivative of the respective measurand (attenuation) with respect to the uncertainty component. The terms used in the calculation of sensitivity coefficients can be seen in equation (5):

\[
\frac{\partial \alpha}{\partial V_{\text{pha}}} = \frac{20\log e}{D \cdot V_{\text{pha}}}; \quad \frac{\partial \alpha}{\partial V_{\text{ref}}} = -\frac{20\log e}{D \cdot V_{\text{ref}}}; \quad \frac{\partial \alpha}{\partial D} = -\frac{20\log V_{\text{pha}} - \log V_{\text{ref}}}{D^2}
\]  

(5)

2.4. Expanded uncertainties

The expression of the expanded standard uncertainty \((U = k \cdot u_c)\) considered the confidence level of 95%. The coverage factor \(k\) depends on the effective degrees of freedom that were calculated by equation (6):

\[
V_{\text{eff}} = \frac{\sum u_i^4}{u_c^4}
\]

(6)

Where \(u_c\) is the combined standard uncertainty of the measurand whose effective degrees of freedom are calculated; \(u_i\) is components of combined standard uncertainty; and degrees of freedom \(v_i\) is component of combined standard uncertainty in question.

3. Results and Discussions

The results were based on data from experiments with silicone phantoms and manufactured in PVCP at LUS / PEB / COPPE / UFRJ. Measurements were made with transducers of 1 MHz. It was considered irrelevant uncertainties due to variation of temperature, relative humidity and no homogeneity of the phantoms in the calculation of the uncertainty. The results of measurements performed using silicone phantoms are on Table 1, while the ones with PVCP phantoms are on Table 2 and can be seen in Figure 3.

Table 1. Silicone phantom uncertainty measurements including signal amplitudes of \(V_{\text{ref}}\) and \(V_{\text{pha}}\), and thickness.

| Greatness | Estimate | Standard uncertainty | Probability distribution | Sensitivity Coefficient | uncertainty contributes | Combined standard uncertainty | Vi | Veff | k | Unc. Exp. 95% |
|-----------|----------|----------------------|--------------------------|------------------------|------------------------|-------------------------------|----|------|---|--------------|
| thickness [cm] – type A | 2.302 | 1.80E-03 | Normal | 5.30E-001 | -9.53E-04 | inf | 1.10E-01 | 1.53E+02 | 2.25 | 0.247 |
| thickness [cm] – type B | 2.89E-04 | 2.89E-04 | Rectangular | -1.53E-04 | 5 |
| Vref [V] – type A | 3.661 | 1.32E-02 | Normal | 1.03E+000 | 1.36E-02 | inf | 1.10E-01 | 1.53E+02 | 5 |
| Vref [V] – type B | 3.50E-02 | 5.50E-02 | Rectangular | 5.98E-02 | 5 |
| Vpha [V] – type A | 2.650 | 2.64E-02 | Normal | 1.42E+000 | 3.76E-02 | inf | 1.10E-01 | 1.53E+02 | 5 |
| Vpha [V] – type B | 5.80E-02 | 5.80E-02 | Rectangular | 8.26E-02 | 5 |
Table 2. PVCP phantom uncertainty measurements including signal amplitudes of Vref and Vpha, and thickness.

| Greatness | Estimate | Standard uncertainty | Probability distribution | Sensitivity Coefficient | Uncertainty contributes | Combined standard uncertainty | Vi | Vreff | k | Unc. Exp. 95% |
|-----------|----------|----------------------|--------------------------|-------------------------|------------------------|-----------------------------|----|-------|---|----------------|
| thickness [cm] – type A | 2.202 | 1.80E-03 | Normal | -1.80E-001 | -3.23E-04 | 1.22E-01 | | | | |
| thickness [cm] – type B | 2.89E-04 | Rectangular | | | -5.19E-05 | | | | | |
| Vref [V] – type A | 3.16 | 3.10E-02 | Normal | 1.06E+000 | 3.30E-02 | 3.73E+02 | | | | |
| Vref [V] – type B | 7.03E-02 | Rectangular | | | 7.47E-02 | | | | | |
| Vpha [V] – type A | 3.36 | 3.10E-02 | Normal | 1.17E+000 | 3.46E-02 | | | | | |
| Vpha [V] – type B | 7.03E-02 | Rectangular | | | 8.26E-02 | | | | | |

Figure 3. Graph presentation of uncertainty components A and B types that contribute to the uncertainty expression of attenuation coefficient.

Comparing Tables 1 and 2 and the graph in Figure 3 it can be seen that the type B standard uncertainty of Vref and Vpha contributes to the combined standard uncertainty of the attenuation coefficient. The value of this quantity was obtained by performing five measurements in the same phantom. Changes in the measurement procedure, for example, increasing the measuring number or even measuring instrument (an instrument with higher accuracy) may allow a reduction in uncertainty.

4. Conclusion

A study of uncertainties in attenuation values of ultrasonic measurement method commonly used in laboratory experiments was conducted. It was found that for the attenuation, the largest uncertainty is due to Vref and Vpha measurements. The uncertainties obtained are less than 1% of the value of measurands for this reason it is possible to consider them acceptable for this experiment.
5. Reference

[1] Takegami K, Kaneko Y, Watanabe T, Maruyama T, Matsumoto Y, Nagawa H. 2004 Polyacrylamide Gel Containing Egg White as New Model for Irradiation Experiments Using Focused Ultrasound. *Ultrasound In Med. & Biol.* Vol. 30, No. 10, pp. 1419-22.

[2] Prokop A F, Vaezy S, Noble M L, Kaczkowski P J, Martin R W, Crum L A. 2003. Polyacrylamide Gel as an Acoustic Coupling Medium for Focused Ultrasound Therapy. *Ultrasound In Med. & Biol.* Vol. 29, No. 9, pp. 1351–58

[3] Zell K, Sperl J I, Vogel M W, Niessner R, Haisch C. 2007. Acoustical Properties of Selected Tissue Phantom. *Physics in Medicine and Biology*. 52 N475–N484.

[4] BIPM 2008 Evaluation of measurement data – Guide to the expression of uncertainty in measurement, JCGM 100: (GUM 1995 with minor corrections), in: *www.bipm.org/en/publications/guides/gum.html*

[5] National Physical Laboratory Npl. 2000. Underwater Acoustics, Technical Guides - Speed of Sound in Pure Water. Teddington, Middlesex, Uk: Npl;