Metrology applied to ultrasound characterization of trabecular bones using the AIB parameter.

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Abstract: Apparent Integrated Backscattering (AIB) presents correlation between Apparent Backscatter Transfer Function and the transducer bandwidth. Replicas of trabecular bones (cubes of 20 mm side length) created by 3D printing technique were characterized using AIB with a 2.25 MHz center frequency transducer. A mechanical scanning system was used to acquire multiple backscatter signals. An uncertainty model in measurement based on the Guide to the Expression of Uncertainty in Measurement was proposed. Initial AIB results are not metrologically reliable, presenting high measurement uncertainties (AIB = -15.1 dB ± 13.9 dB). It is noteworthy that the uncertainty model proposed contributes for metrological assessment of trabecular bone characterization using AIB.

Keywords: Quantitative Ultrasound (QUS), Apparent Integrated Backscattering (AIB), Trabecular Bones, Measurement Uncertainty

1. INTRODUCTION

The Quantitative Ultrasound (QUS) was introduced around the 1980s to clinical evaluation of bone health conditions [1]. The acoustic properties of trabecular bone have been widely investigated in vitro. Using pulse-echo methods, there are many parameters that can be determined. In this paper, the parameter that will be considered is AIB – Apparent Integrated Backscatter. Previous studies indicate a significant potential of this parameter to reflect structure, density, composition and mechanical properties of trabecular bones [2]. However, it can not be found in literature metrological reliable results.

Therefore, standard samples were developed to imitate healthy human trabecular bones and also with osteoporosis with propose to obtain a reference material to be used to ensure measurements with metrological quality.

The measurement uncertainty has a great importance in the characterization of the samples because it is possible to detect how much the value scatters around the mean.

2. MATERIALS AND METHODS

2.1. Samples

Isotropic bone replicas were produced in acrylonitrile butadiene styrene polymer (ABS) using 3D printing technique at CTI Renato Archer, Campinas. They are cubes of 20 mm × 20 mm × 20 mm (Figure 1).

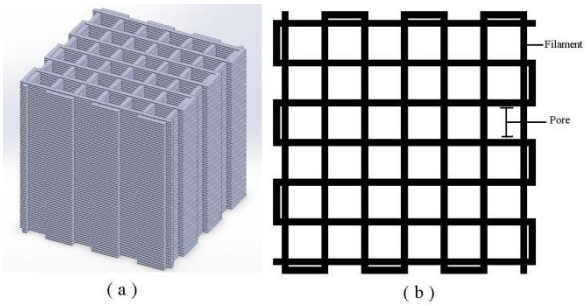

Figure 1. Bone replica form and structure.

The samples were distinguished by pore size and filament size (in mm); see Table 1.

Table 1. Isotropic bone replica structure.

Sample	Pore size [mm]	Filament size [mm]
0.5_0.2032	0.5	0.2032
0.5_0.5782	0.5	0.5782
2.5_0.2782	2.5	0.2782
2.5_0.5282	2.5	0.5282

2.2. Measurement system

The measurement system consists of a 2.25 MHz central nominal frequency transducer, an arbitrary waveform generator (Agilent 33250A), an oscilloscope (Agilent DSO 6032A), a water tank (240 mm × 240 mm × 240 mm) filled with deionized water and a polished steel plate reflector (Ø 63 mm × 10 mm) (Figure 2).

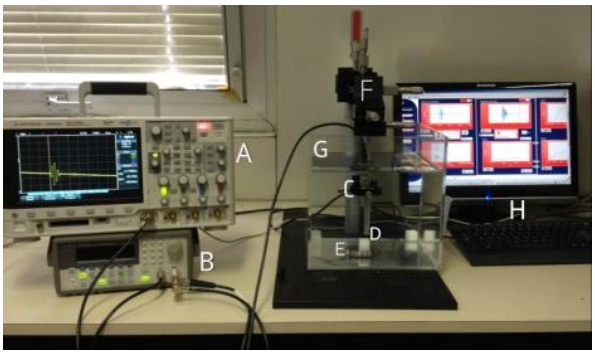

Figure 2. Measurement System: A- Oscilloscope, B- Arbitrary waveform Generator, C- Transducer, D- Bone replica sample, E- Reflector, F- Linear and angular stages, G- Water tank, H- Computer.

Measurements were made using a system with three linear stages; 25.4 mm travel each, responsible for transducer movement in three different axes (x, y, z) and two goniometric stages, ± 5º travel that are responsible for transducer alignment with reflector.

2.2. Methodology

The sample was degassed under vacuum and placed on the bottom of water tank at 22 °C [4].

The transducer was positioned in the near field from the front surface of reflector to acquire a reference signal. The operator has used a software, developed in LabView, to select a time window gate. This procedure was used to acquire the initial of backscattering signal situated after sample surface signal until initial reflector signal. FFT (Fast Fourier Transform) was performed and it was determined the transducer -6 dB bandwidth. The sample was positioned with the surface parallel to transducer surface, within the near field produced by the transducer. After that, the power spectrum of the signal backscattered from the sample was obtained through a similar procedure, except that the gate was delayed to verify that no energy from the surface reflection was incorporated in the sample-backscattering window. This signal is called sample signal. So, using these two signals, the parameters can be calculated.

The measurements were performed in the four sides of cube, which have the same physical architecture. It was carried out 9 measurements per side.

2.4. Characterization parameters

The AIB was determined by integrating the Apparent Backscatter Transfer Function (ABTF), over the -6 dB bandwidth of the transducer, this can be viewed in the equation 1 [2]:

$$AIB = \frac{1}{\Delta f}\int_{\Delta f} ABTF\ df \qquad (1)$$

Where:

Δf – The transducer bandwidth.

And,

$$ABTF = 10 \times log\left(\frac{A_b}{A_r}\right) \quad (2)$$

Where:

A_b – Power spectrum of the sample in the acoustic path;

A_r – Power spectrum of the reference signal.

The AIB informs the mean value of apparent backscattering in the bandwidth of transducer used.

2.5. Measurement uncertainty

It was used the Guide to the expression of uncertainty in measurement (GUM) to express the uncertainty of measurement result [5].

The measurement uncertainty was obtained considering Type A standard uncertainty and Type B standard uncertainty. Type A standard uncertainty was obtained from standard deviation divided by $\sqrt{9}$. Type B evaluation of standard uncertainty was obtained from the amplitude expanded uncertainty, in volts, from oscilloscope certificate divided by $k = 2$.

Type A and Type B standard uncertainties were combined as can be viewed in equation 3.

$$u_c = \sqrt{(u_{type\,A} \times c.s_A)^2 + (u_{type\,B} \times c.s_B)^2} \quad (3)$$

Where:

u_c – combined uncertainty;

$c.s_A$ - Sensitivity coefficient to Type A standard uncertainty;

$c.s_B$ - Sensitivity coefficient to Type B standard uncertainty.

The coverage factor k was determined from effective degrees of freedom and the level of confidence equal to 95%. Expanded uncertainty U can be given by equation 4.

$$U = u_c \times k \quad (4)$$

Thus, this expanded uncertainty relates one side of one sample result, so there are four expanded uncertainty for each sample. The final combination of uncertainties was assessed with side combined uncertainties by their effective degrees of freedom according to equation 5.

$$u_{C_G} = \frac{v_1u_1+v_2u_2\ldots v_nu_n}{v_1+v_2+\cdots v_n} \quad (5)$$

Where:

u_{C_G} – global combined uncertainty;

$v_1, v_2 \ldots v_n$ - effective degrees of freedom;

$u_1, u_2 \ldots u_n$ – combined uncertainty.

So the coverage factor k was determined and the global expanded uncertainty U_G was calculated.

To compare the results obtained by each side, the measurements were compared with the global result of sample using the standardized error E_n as defined in equation 6. Values are considered statistically equal if the E_n is less or equal to 1.

$$E_n = \frac{X_G - X_S}{\sqrt{U_G^2 + U_S^2}} \quad (6)$$

Where:

E_n – normalized error;

X_G – global mean (sample mean);

X_S – side mean;

U_S – side measurement uncertainty;

3. RESULTS

Table 2 provides Apparent Integrated Backscatter results accompanied by coverage factor and measurement uncertainty values of trabecular bones samples measurements and normalized error between each side.

Table 2. Results of trabecular bones samples measurements

Sample	Side	X (dB)	k	U (dB)	E_n Satisfactory? 1	2	3	4
0.5_0.5782	1	-17.2	2.14	0.22	X	Not	Yes	Yes
	2	-16.1	2.20	0.29	Not	X	Not	Not
	3	-17.1	2.26	0.54	Yes	Not	X	Yes
	4	17.6	2.31	0.63	Yes	Not	Yes	X
2.5_0.5282	1	-13.6	2.31	0.59	X	Yes	Yes	Not
	2	-13.5	2.31	0.47	Yes	X	Yes	Not
	3	-13.7	2.26	0.45	Yes	Yes	X	Not
	4	-12.4	2.09	0.12	Not	Not	Not	X
0.5_0.2032	1	-16.7	2.31	0.68	X	Not	Yes	Not
	2	-13.9	2.00	0.20	Not	X	Not	Yes
	3	-15.9	2.26	0.76	Yes	Not	X	Not
	4	-14.1	2.31	0.68	Not	Yes	Not	X
2.5_0.2782	1	-13.5	2.31	0.32	X	Not	Not	Not
	2	-12.6	2.26	0.24	Not	X	Not	Not
	3	-13.0	2.20	0.17	Not	Not	X	Not
	4	-17.3	2.20	0.34	Not	Not	Not	X

Analysing Table 2, it is possible to realize that there are many results not equal statically. To solve this, it was created a multiplier factor *MF* used to increase the global expanded uncertainty and make equal results, as can be seen in Table 3.

Table 3. Results with multiplier factor

Sample	Side	MF	X_G (dB)	k_G	U_G (dB)	E_n	Satisfactory?
0.5_0.5782	1	2.22	-17.0	2.02	4.2	0.32	Yes
	2					1.00	Yes
	3					0.06	Yes
	4					0.30	Yes
2.5_0.5282	1	5.45	-13.3	2.01	12.3	0.07	Yes
	2					0.05	Yes
	3					0.12	Yes
	4					1.00	Yes
0.5_0.2032	1	4.45	-15.1	1.99	13.9	0.35	Yes
	2					1.00	Yes
	3					0.16	Yes
	4					0.24	Yes
2.5_0.2782	1	6.70	-14.1	2.02	8.0	0.21	Yes
	2					0.68	Yes
	3					0.68	Yes
	4					1.00	Yes

Table 4 is responsible to show E_n results combining each sample to demonstrate if the characterization method can detect differences between samples used.

Table 4 - E_n of samples combination

Samples Combination	*En*	*Satisfactory*?
0.5_0.5782/2.5_0.5282	0.3	Yes
0.5_0.5782/0.5_0.2032	0.1	Yes
0.5_0.5782/2.5_0.2782	0.3	Yes
2.5_0.5282/0.5_0.2032	0.1	Yes
2.5_0.5282/2.5_0.2782	0.1	Yes
0.5_0.2032/2.5_0.2782	0.1	Yes

4. DISCUSSION AND CONCLUSION

The isotropic bones replica should provide results statistically similar for all the sides, but the results in Table 2 show that the samples 0.5_0.5782 and 2.5_0.5282 present different results for sides 2 and 4, respectively.

The samples 0.5_0.2032 and 2.5_0.2782 have 0.2 mm-thickness filaments, which are, as expected, thinner than the applied ultrasound wavelength. This can explain why they are not statistically similar.

Assuming that the samples were structurally isotropic, the multiplier factor was applied in order to make all samples side results statistically equal, and the bone replica global uncertainty possible to be estimated (Table 3). High values of expanded uncertainty were obtained for all samples. Therefore, these results are not metrologically reliable. Moreover, Table 4 displays that all results are statistically equal showing that this method cannot be able to identify and classify different bone replica architecture, as it is expected for. Besides, the results associated with its respective uncertainties demonstrated that it is not possible to relate the AIB with BMD (Bone mineral density), as it was established in the literature [3].

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