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Arterial diameter measurement using high resolution ultrasonography: *In vitro* validation

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***Abstract*— Simultaneous measurement of pressure and diameter in blood vessels or vascular prosthesis is of great importance in cardiovascular research. Knowledge of diameter changes as response to intravascular pressure is the basis to estimate the biomechanical properties of blood vessel. In this work a new method to quantify arterial diameter based in high resolution ultrasonography is proposed. Measurements on an arterial phantom placed on a cardiovascular simulator were performed. The results were compared to sonomicrometry measurements considered as gold standard technique. The obtained results indicate that the new method ensure an optimal diameter quantification. This method presents two main advantages respect to sonomicrometry: is noninvasive and the vessel wall strain can be measured directly.**

I. INTRODUCTION

SIMULTANEOUS measurement of pressure and diameter of blood vessels and/or vascular prosthesis is of great importance in cardiovascular research because they allow submitting vessels and/or prosthesis to controlled experimental conditions. Knowledge of diameter changes as response to intravascular pressure is the basis to estimate biomechanical properties (e.g. elasticity, viscosity) of the vessel. To evaluate the vascular biomechanics under pharmacologic stimuli, tissue preservation procedures, physiologic/pathologic changes (i.e. changes in pressure, flow or cardiac frequency) it requires systems capable of estimate the instantaneous diameter in dynamic *in vitro* studies [1-3]. Thus having tools that allow a precise and adequate estimation of the diameter dynamics, but at the same time, that do not disturb the vessel itself is of great importance in cardiovascular research.

Sonomicrometry is a technique considered as gold standard to estimate vascular diameters. It is based on the measurement of the time-of-flight of an ultrasound pulse between two piezoelectric crystals sutured or glued in opposite sides of the arterial wall [1-3]. Although it is widely used in cardiovascular research, it has some limitations which determine the need of searching for new techniques that overcome them. Among these limitations it can be mention the need to adhere the ultrasonic transducer to the vessel's wall. This procedure can disturb the stress distribution of the wall. In addition, it is difficult to change the measurement position (for example to estimate the diameter in different segments shortly separated); finally one major limitation is the impossibility of the method to measure directly the internal diameter and wall thickness.

An alternative method that overcomes the limitations above, and allows dispensing with sonomicrometry, is to use high resolution ultrasonography. The dynamics of vessel's diameters can be measured by correlation of RF ultrasonic data (A-Scan). However, to bring reliable results, this method has to be validated against sonomicrometry. The goal on this work is to evaluate the performance of high resolution ultrasonography in estimating diameters and compare the results with gold standard measurements (sonomicrometry).

II. EXPERIMENTAL SETUP

A hollow cylinder made with PVA (Hidrolized PolyVinilic Alcohol) was used as an arterial mimicking phantom [4]. The sample has 5 mm in internal diameter, 2.5 mm wall thickness and 70 mm length. For its elaboration 10% w/w of PVA was diluted in hot water at 90ºC. For polymerization, the solution was submitted to 7 cycles of freeze-unfreeze of 12 hours each. The number of freeze-unfreeze cycles is directly related to the final stiffness. Thus, 7 cycles is enough to bring the sample a Young modulus comparable to that of real arteries having the similar dimensions.

The sample was placed in a cardiovascular simulator designed for measuring pressure and instantaneous diameter in blood vessels and prosthesis (Fig. 1). The simulator consists basically in an artificial heart (model Jarvik 5, Kolff Medical, Salt Lake City, UT) coupled to a perfusion line made of polyethylene and silicone.

The artificial heart is composed by in/out valves and two chambers separated by a mobile diaphragm. The fluid flows within the chamber containing the in/out valves while the other is connected to a pneumatic pump adapted from a mechanical respirator. The cardiac frequency, pressure amplitude and systole/diastole width can be controlled by

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the pump. In the present work 3 pumping frequencies were used: 72, 96, and 132 beat per minute (bpm). They were chosen in order to comprise a wide physiologic range. The perfusion line ends in a reservoir whose height determines the base pressure level. The amplitude of the pressure wave depends on the air volume injected by the pump. In this work several pressure levels were used to comprise a wide physiological range (Table 1).

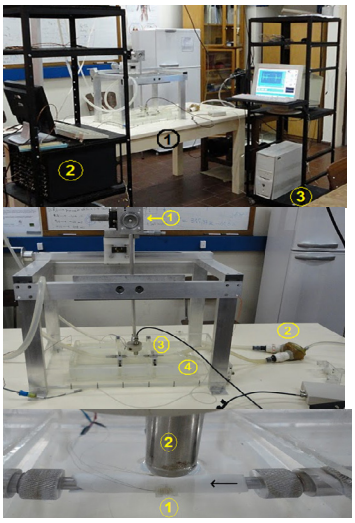

Fig. 1. **Top:** Laboratory and experimental setup equipment. 1: Cardiovascular simulator. 2: System 6. 3: High resolution ultrasonography electronics. **Middle:** Cardiovascular simulator. 1: Ultrasonic transducer positioning system. 2: Artificial Heart. 3: Sample holding system. 4: Lateral entry of pressure sensor **Bottom:** PVA sample (White cylinder) mounted between metallic connectors of perfusion line and measurement system. The arrow indicates the flux sense. 1: sonomicrometry crystal (The other one is on the opposite side of the phantom). 2: Ultrasonic transducer (A-Scan).

The container holding the sample under investigation is after the pump and the artificial heart (Fig 1). The container is filled with distilled water which is used as the propagating medium of ultrasonic pulses. A solid state pressure sensor (Model 2.5; 1200 Hz response frequency, Königsberg Instruments, Inc., Pasadena, CA, USA) is positioned inside the sample through a catheter. It is located close to the place where diameter measurements are made. The pressure signal is acquired by the pressure modulus of System 6 electronics (Tryton Technology Inc., San Diego, CA, USA) using 200 Hz sampling frequency.

A. Diameter estimation using ultrasound (A-Scan)

Based on the works of Hasegawa et al. [5, 6], the authors implemented a method to estimate diameters using backscattering RF signals (A-Scans) [7, 8]. In this work a 10 MHz central frequency ultrasonic transducer (Panametrics V312) is used. It was mounted on a positioning system independent of the cardiovascular simulator. This system allows orientating the ultrasound beam perpendicular to the sample axis along a diameter (Fig. 1). Once the transducer is on its final position, the RF backscattered signals are acquired at 80 MHz sampling frequency with a pulse repetition frequency (PRF) of 20 Hz. In each A-Scan, 4 echoes are clearly seen, corresponding to the fluid-vessel wall interface. Fig. 2 displays a schematic representation of the measurement procedure.

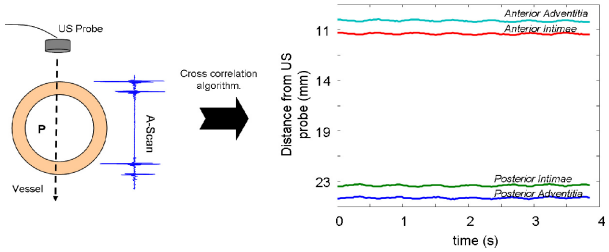

Fig. 2. Schematic representation of the ultrasonic method (A-Scan).

The diameter is estimated from these 4 echoes position by using a correlation algorithm between consecutives A-Scans [9, 10]. The first step of this algorithm consists in selecting the echoes of those 4 interfaces. In this work it was done manually by picking them from the plot in the screen. This selection is saved in order to keep the initial position of each interface. The second step consists in cross-correlating the echoes in consecutive A-Scans for different time lags. The maximum of the correlation coefficient gives the time-shift δt between signals. This value can be converted to displacement using the ecographic mode formula $\delta z = c\delta t/2$, where c is the sound speed in the medium (~1.5 mm/μs). In order to improve the time-shift estimation a parabolic interpolation around the maximum of the correlation coefficient is used. The third and final step of the algorithm consists on an extension of the second step to the whole set of acquired A-Scans. The final result is the time-dependence of each interface position. From this data the external and internal diameter as well as the wall thickness can be

TABLE I

SUMMARY OF EXPERIMENTAL CONDITIONS

Beat per minute	Max/Min Pressure Level (mmHg)	Max/Min Sonomicrometry Diameter (mm)	Max/Min A-Scan Diameter (mm)	Slope	Intercept (mm)
132	80 / 50	11,43 / 11,29	11,73 / 11,54	0,998	0,286
132	70 / 30	11,34 / 11,14	11,78 / 11,53	0,994	0,32
132	125 / 85	11,71 / 11,53	12,08 / 11,77	1,011	0,156
96	70 / 30	11,31 / 11,05	11,52 / 11,21	0,976	0,43
72	80 / 20	11,83 / 11,52	11,81 / 11,39	0,969	0,285

extracted as function of time. It is noted therefore that this method gives extra information with respect to the sonomicrometry measurements.

B. Diameter estimation using sonomicrometry

Sonomicrometry is used to estimate the distance between two small ultrasound crystals implanted in the tissue. It is considered as a gold standard technique for diameter estimation with ultrasound. The instantaneous distance between crystals is estimated by the time-of-flight of an ultrasonic pulse traveling between them (Fig. 3).

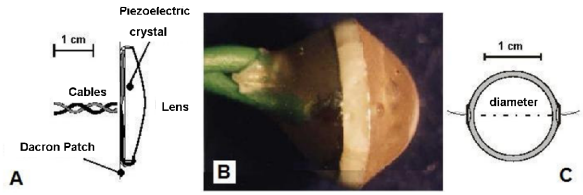

Fig. 3. **A:** Scheme of an ultrasound crystal used for vessel diameter estimation. **B:** Magnified picture of one ultrasound crystal. **C:** Schematic representation of the positioning of each crystal in a blood vessel.

The time-of-flight is calibrated for a known distance using a sound speed value of 1.5 mm/μs. The ultrasound crystals, made of PZT, are circular shaped with diameter between 2 and 7 mm. Their central frequency is 5 MHz. The faces of the piezoelectric crystal are covered with a polyurethanic resin with semi-spherical shape which acts as lens. The emission-reception electronics is the sonomicrometry modulus of the System 6 (Tryton Technology Inc., San Diego, CA, USA). This modulus has an independent calibration system which allows distance measurements between 2 and 123 mm.

The piezoelectric crystals have a Dracon patch above the lens. Thus, they can be sutured to the vessel wall using non-perforating points. Once the first crystal is sutured, the other one is moved around the opposite side of the vessel in order to find the maximum signal but also looking for the maximum distance to guarantee a diameter measurement. An A/D converser was used to digitize the sonomicrometry signal at 200 Hz sampling frequency.

C. Recording protocol and Pre-signal processing

The PVA sample was subjected to pressure, flow and frequency conditions simulating real situations (Table I). The records duration was between 10 and 20 beats. Experiments with different pumping frequency, mean pressure level and pressure amplitude were made in order to test the A-Scan method under a variety of conditions.

As mentioned above, in each experiment 10-20 beats were recorded continuously using sonomicrometry (A-Scan off), then 10-20 beats with both methods simultaneously and finally 10-20 beats using A-Scan (Sonomicrometry off). The simultaneous records are not useful because the ultrasound signal of one method interferes with the other due to the close bandwidth of both electronics. Thus separated records were compared. In addition, sonomicrometry records were under sampled to meet 20 Hz. Under such conditions both measurements can be quantitatively compared.

III. RESULTS

The obtained external diameter signals are shown in Fig. 4. Both signals are clearly correlated. By performing a Fourier transform of both signals the power spectrum is obtained (Fig. 5). From both figures not only a coincidence in time domain is obtained but also in the frequency domain. A plot of the diameter estimated by the A-Scan method vs the diameter obtained with sonomicrometry is displayed in Fig. 6. The slope of the curve for this particular case is 0.9944 (p = NS respect to unity). The residues distribution is also presented in Fig. 6 (right). The distribution is Gaussian distributed with mean value of 0 and standard deviation of 0.02 mm. Results under other experimental conditions are summarized in Table I. A mean slope of 0.9896 with a standard deviation of 0.017 is obtained from all cases. A non-zero intercept term (0.295 ± 0.098) mm is due to the presence of a systematic error. This could be due to a misalignment of the ultrasonic probe, piezoelectric crystals or anisotropy of the sample.

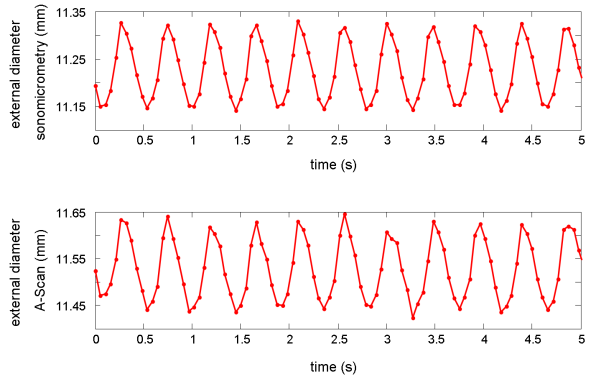

Fig. 4 **Top:** Diameter dynamic estimation by sonomicrometry. **Bottom:** Diameter dynamic estimation by A-Scan.

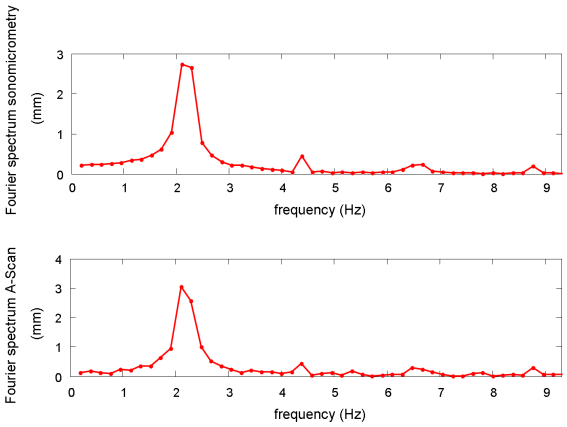

Fig. 5. Power spectrum computed from fast Fourier transform of signals in Fig 4.

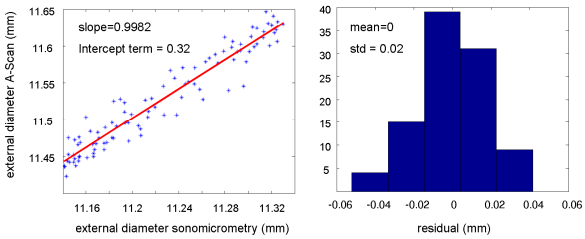

Fig. 6. **Left:** Correlation between diameter estimations using A-Scan and sonomicrometry. **Right:** Residual distribution represented as a histogram.

The A-Scan method posses some advantages over the sonomicrometry technique. Among these advantages the most important one is the fact that the internal diameter and the strain of the arterial wall can be measured directly. In the case of sonomicrometry this can be done indirectly through calculations assuming a cylindrical shell model of constant density. In Fig. 7 the internal diameter and the phantom strain are presented as a function of time for the same signals presented in Fig. 4.

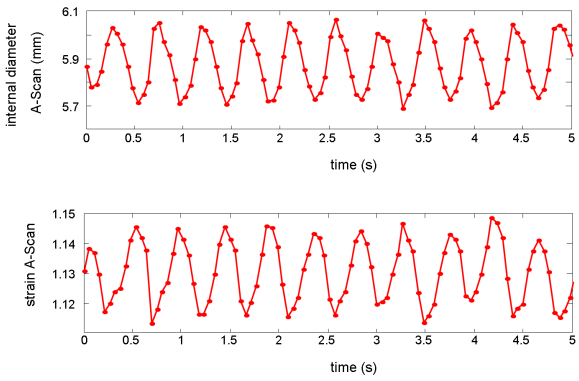

Fig. 7 **Top:** Internal diameter measurement using ultrasonography. **Bottom:** Strain measurement derived from internal and external diameter measurement using ultrasonography.

IV. CONCLUSIONS

A new method to estimate vascular diameters using high resolution ultrasound is presented. Results were validated against sonomicrometry which is considered as a gold standard method. External diameter signals are closely related when compared in time and frequency domain for both techniques. The residuals present a Gaussian distribution with mean value zero, which is indicative of random errors only.

The proposed method posses several advantages: firstly it does not disturb the stress distribution of the blood vessel. Secondly extra information can be obtained like the variation of internal diameter and wall strain. This information is useful for the assessment of the biomechanical properties of the sample.

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