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Modal Analysis of Ultrasound Radiation Force Generated Shear Waves on Arteries

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***Abstract*—Arterial elasticity has gained importance in the past few decades as a predictor of cardiovascular diseases and mortality. Measuring the speed of propagation of the pressure wave traveling in the wall of the arteries has been used for a very long time to estimate the mechanical properties of the artery. Two of the major disadvantages of this method are the low temporal resolution (1 sample per second) and the low spatial resolution (carotid-femoral or carotid-radial segments). In our laboratory, we have been working on an ultrasound radiation force-based method to generate high frequency local shear waves, which will allow the study of the mechanical properties of short arterial segments within the heart cycle. In this work we present a modal analysis of the waves generated by our method on an excised pig artery. By doing a two-dimensional fast Fourier transform (2D FFT) of the propagating waves, it was possible to differentiate the multiple Lamb-like modes propagating in the wall. These modes showed changes with varying transmural pressure; this was expected as the arterial stiffness increases with pressure. This work shows the feasibility of our method for the study and characterization of propagating modes in the arterial wall. Future studies include developing a Lamb wave model for cylindrical viscoelastic structures to fit our data.**

I. Introduction

THE interest in arterial elasticity as a predictor of cardiovascular disease and mortality has increased in the past few decades [1, 2]. Increased arterial stiffness also been associated with coronary events and stroke [3]. Since the 1930's the speed of propagation of the pressure wave has been associated the elasticity of arteries, this has been widely used and it is referred as pulse wave velocity. Even though this technique has allowed the study of mechanical properties of arteries, it has several disadvantages that have prevented it from becoming a clinical tool. One of the drawbacks is its low temporal resolution (about 1-2 Hz) which is dependent on the heart rate. This makes this technique not suitable to study the changes in elasticity within the heart cycle. Another difficulty with this method is the low spatial resolution due to the long wavelength of the pressure wave (2.5 to 5 m) which requires long distances to accurately measure the time of travel between two points. Consequently, it is useful to evaluate long segments (carotid-femoral or carotid-radial) or global elasticity. In this work we present an ultrasound radiation force base technique to generate localized shear waves with high temporal resolution. The localized waves allow the study of short segments, therefore the ability of characterize the mechanical properties of different vessels throughout the body. At the same time the high temporal resolutions makes this methodology applicable in the study of dynamic arterial properties (throughout the heart cycle). In this work, we also propose a method for analyzing the type of waves propagating over a short distance (1-2 cm) in the arterial wall This is of great importance since the speed of propagation can vary depending on the mode that is being measure, and since the speed at which these waves travel is use to estimate the elasticity of arteries [4], then it becomes imperative to know which mode is being measured.

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II. Methods

A. Theory

The speed of propagation of a wave can be determined by measuring the time it takes to travel from point A to point B. This is possible when the wave is composed by a single mode or a single wave. In the case of multiple modes propagating simultaneously, measuring the speed of propagation in the time domain can produce over or underestimation of the true values. This can be solved by looking at the data in the wave number/frequency domain, where the modes can be differentiated and the speeds for each mode can be determine [5]. In our study we performed a two-dimensional (2D) Fourier transform of the form,

$$H(k,f)=\sum_{m=-\infty}^{+\infty}\sum_{n=-\infty}^{+\infty}u_z(x,t)e^{-j2\pi(kmx+fnt)} \quad (1)$$

were $u_z(x,t)$ is the motion of the arterial wall in the radial direction (z), which is a function of distance along the artery (x) and time (t), k is the wave number and ω is the temporal frequency of the wave. Equation (1) allows a simultaneous representation of the spatial and temporal-frequency domain of the propagating waves. Fourier transforms were performed by fast Fourier transform algorithm in MATLAB (The Mathworks, Natick, MA).

B. Experiments

The purpose of the experiment was to measure the speed of propagation of the different modes of propagating waves on the arterial wall. The model in our experiments was an excised pig carotid artery. The artery was stretched to 140% of the recoiled length, and was mounted on a frame. The vessel was embedded in a tissue mimicking gelatin and cannulated on both ends. One of the ends was attached to a column of saline solution in order to vary the transmural pressure. The phantom was immersed in a water tank where a 3 MHz confocal transducer and a 7.5 MHz pulse-echo transducer were cofocused on the arterial wall. To generate the localized wave a 3 MHz, 200 μs toneburst was applied to the confocal transducer, and transmissions were repeated at a 50 Hz rate to concentrate energy at this frequency as well as harmonics of this frequency up to 2 kHz. The confocal transducer was tilted at a 30 degree angle with the vertical axis. To measure the propagation of the generated waves, 21 points separated by 1 mm, were investigated with a pulse-echo transducer oriented parallel to the vertical axis (orthogonal to the length of the artery). Since the properties of arteries vary with transmural pressure [6] we explore the effect of this on the speed and modes of propagation. We repeated the excitation and acquisition at different transmural pressures, starting at 10 mmHg and going up to 100 mmHg in 10 mmHg increments. Figure 1 shows a representation of the setup.

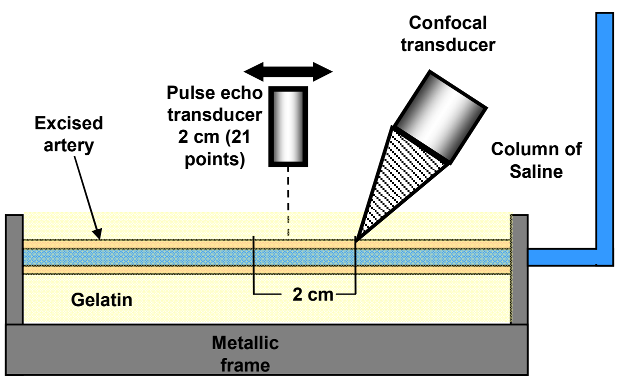

Fig. 1. Representation of the experimental set up for an excised pig carotid. Shear waves were generated using a confocal transducer and the propagation of the wave was measured with an ultrasound pulse echo system.

III. Results

In Figure 2 is a representative plot of the propagation of the shear waves generated with radiation force on the arterial wall. The *x*-axis represents the time of propagation, and the *y*-axis is the distance (in mm) between the focal regions of the confocal transducer and the pulse-echo transducer.

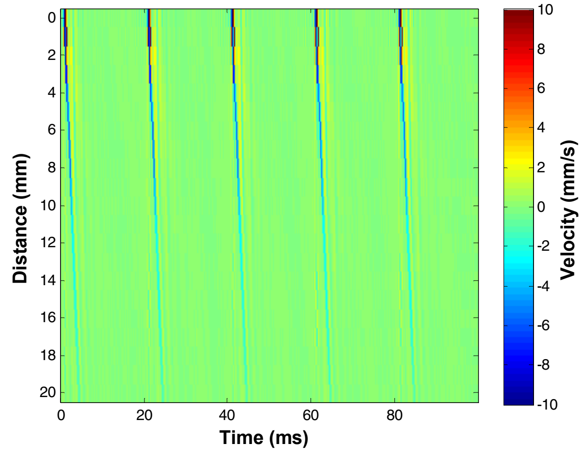

Fig. 2. Shear wave propagation on the front wall of excise pig carotid.

In Figure 3, the propagation of the first impulse in the artery wall is depicted. Panels A, B and C correspond to the three transmural pressures (10, 50 and 100 mmHg).

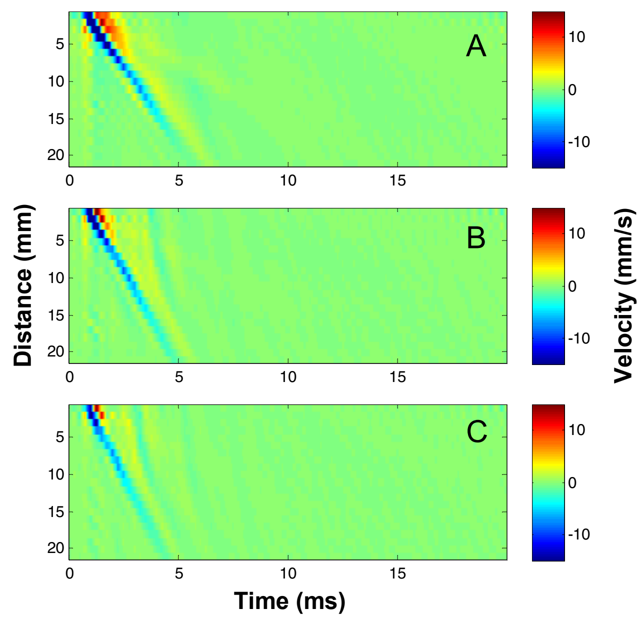

Fig. 3. Propagation of first impulse in the arterial wall at different pressures. Panel A represents the 10 mmHg, B, 50 mmHg and C, 100 mmHg.

Figures 4A, 4B and 4C, shows the 2D FFT of the first excitation for 3 different transmural pressures (10 (A), 50 (B) and 100 mmHg (C)). The *x*-axis represents the temporal frequency of the signals and *y*-axis represents the wavelength ($\lambda = 1/k$) of the waves.

Figure 5 shows the corresponding dispersion diagrams for 10 (A), 50 (B) and 100 mmHg (C). The solid black circles in the graphs represent the peak of the magnitude at each frequency. These graphs are created by identifying where in the frequency-wavelength space there is sufficient magnitude from the propagating waves.

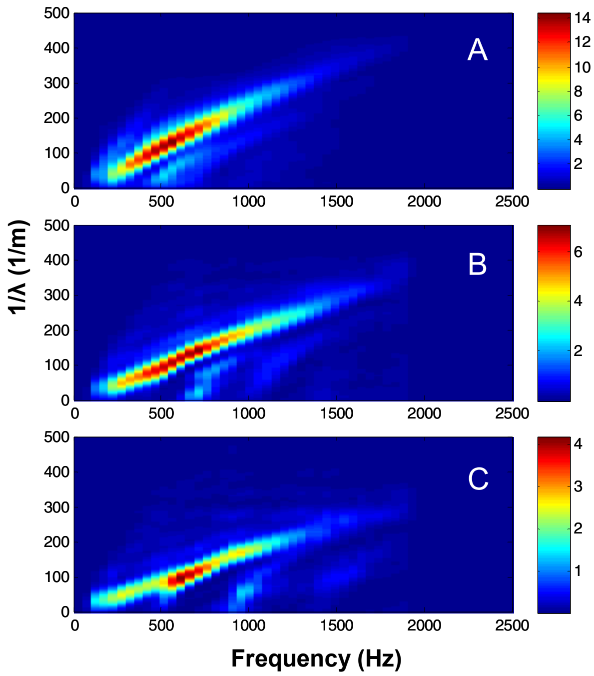

Fig4. Two dimension FFT representation of waves propagating on the arterial wall. Panels A, B and C show the results for 10, 50 and 100 mmHg respectively.

The criterion for determining the presence of sufficient magnitude was a magnitude greater than 90% of the maximum magnitude. At those sites where there is sufficient wave magnitude, the speed of propagation is calculated as $c = \lambda f$, where $1/\lambda$ is the y-axis of the 2D FFT plots, and f, the x-axis.

IV. Discussion

The propagation of the wave travelling in the artery wall generated by the radiation force was shown in Figure 2. Notice how each wave is generated every 20 ms, therefore potentially we could generate 50 waves per second, which would be more than enough to characterize the arterial properties within the heart cycle. Also, it is important to note how in Figure 3 it is not possible to identify the different propagating modes for any of the 3 pressures (10 (A), 50 (B) and 100 mmHg (C)). Calculation of the group velocity from this kind of data could potentially lead to under or overestimation of material property values based these speed calculations if the modes that are present are unknown. This highlights the importance of the modal analysis so that the group velocity can be interpreted appropriately and the modal content is better understood.

Figure 4 shows the 2D FFT, or k-space, representation of a multimodal propagating wave. Note how in the panel A (10 mmHg) aside from the main zero-order anti-symmetric (A0) Lamb-like mode (the strong diagonal segment), a higher order mode can be identified at around 500 Hz. This mode's

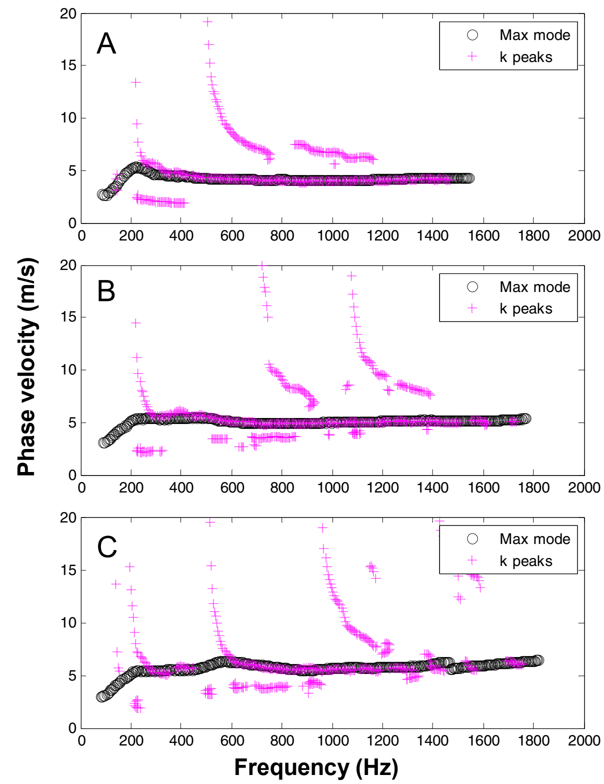

Fig. 5. Dispersion curves for different pressures calculated from the 2D FFT (k-space) plots. Panel A, B and C show the dispersion curves with different propagating modes for 10, 50 and 100 mmHg respectively. The solid circles show the prevalent mode for each frequency while the magenta crosses show the other modes propagating at each frequency.

frequency shifted to around 700 Hz for 50 mmHg (Panel B) and then to 1000 Hz for 100 mmHg (Panel C). This behavior is similar to higher order modes seen in Lamb wave theory, where the frequency at which higher modes appears increases as the stiffness of the material increases.

The different modes can be better appreciated in Figure 4, where the speeds at which each mode propagates is shown in a dispersion graph. Due to the dynamic load produced with the radiation force, where both walls are moving in the same direction, the main propagating mode is an A0 like mode. This mode is identified by the black solid circles in each of the panels. Also to note, this mode increases in speed of propagation at higher frequencies from 4.1 m/s, at 10 mmHg, to 4.95 m/s at 50 mmHg and 5.5 m/s at 100 mmHg.

This work shows localized, high temporal resolution shear waves that can be potentially used in the study of mechanical properties of artery. This method could potentially solve some of the limitations that methods like pulse wave velocity have. We also showed how the application of the 2D FFT can help identify the different propagating modes, which can give a better insight to the mechanical properties of the material being studied. In our case, the modes were Lamb wave-like, therefore future work will be to develop a viscoelastic Lamb wave model for cylindrical structures.

V. CONCLUSIONS

Arterial elasticity has gained importance as a predictor of cardiovascular diseases and mortality. Unfortunately there are no current methods that permit the measurement of elasticity in arteries in a noninvasive, reproducible, high temporal, high spatial resolution. In this work we showed a technique that has the potential to overcome these limitations. At the same time we showed a method to study the modes of shear wave propagation in arterial wall, and how it this kind of analysis can be potentially used to better asses the mechanical properties.

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