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Modal analysis on arteries and tubes using ultrasound vibrometry

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ABSTRACT

Introduction. Arterial elasticity has been proposed as an independent predictor of cardiovascular diseases and mortality. Measurement of the wave speed dispersion for different modes of propagation in thin shells can be used to estimate elastic properties of these structures. Using ultrasound radiation force, it is possible to generate local shear waves which can be tracked with pulse-echo ultrasound to measure their speed of propagation. In the present work, we present a modal analysis performed on an elastic tube and an excised pig carotid artery that can be use to estimate the elastic properties. Methods. A urethane tube and an excised artery were mounted in a metallic frame, cannulated and embedded in tissue-mimicking gelatin. Shear waves were generated in the wall of the tube/artery using a 3 MHz confocal transducer with a 200 µs toneburst, repeated at a rate of 50 Hz. The propagation was measured using pulse-echo ultrasound at 21 locations along the vessel wall spaced 1 mm apart. The transmural pressure was varied from 10 to 100 mmHg in 10 mmHg increments using a column of water. Results. The group velocity of the shear wave for the tube and the artery were significantly different, around 11 m/s for the tube and 5 m/s for the artery. The speed of propagation in the tube showed no variation with increasing tranmural pressure, while in the group velocity of the artery increased from 4 m/s at 10 mmHg to 6.2 m/s at 100 mmHg. The modal analysis using a 2D FFT of the spatio-temporal signal in the tube showed a unique antisymmetric Lamb wave-like mode that was almost invariant with pressure. Meanwhile, the artery exhibited multiple modes, antisymmetric and symmetric like modes, that varied with pressure. Conclusion. Radiation force is a useful technique to generate localized shear waves in cylindrical shell structures. The changes in the observed dispersion curves in the arteries are very encouraging, suggesting that this methodology has potential use in the study of arterial elasticity.

INTRODUCTION

Arterial elasticity has been shown to be a useful predictor of cardiovascular diseases and mortality [1-4]. For several decades the speed of propagation of the arterial wave (pulse wave velocity) has been used to investigate the elastic properties of arteries [5]. Even though this technique has allowed the study of mechanical properties of arteries, there are several disadvantages that have prevented its use as a clinical tool. One of the pitfalls is its low temporal resolution (about 1-2 Hz) which is dependent on the heart rate. This does not allow the technique to be used in the study the of the elascity changes within the heart cycle. Another drawback of this method is the low spatial resolution due to the long wavelength of the pressure wave (2.5 to 5 m). Therefore this technique requires a long segment to be explored, so that the time of travel between the two points measured can be accurately determined. Consequently, pulse wave velocity is generally used to evaluate long segments like carotid to femoral or carotid to radial or and therefore is an estimate of a global elasticity. In this work, we present technique that uses radiation force to generate localized shear waves, with a high bandwith, therefore solving the low spatial and termporal resolution disadvatantges. In this work, we also show some of the results in the modal anlysis of this shear waves in excised arteries as well as in urethane tubes which will be useful in the characteriztion of the mechanical properties of ateries and cylindrical structures.

METHODS

Theory

Determining the speed of propagation of a wave can be done by measuring the time it takes to travel from point A to point B, given that the distance between these two points is known. 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 due to the different speeds of propagation of the different modes. This can be solved by looking at the data in the wave number and frequency domain (k-space), where the modes can be differentiated and the speeds for each mode can be determined [6]. In our study we performed a two-dimensional (2D) discrete Fourier transform of the form,

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

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).

Experiments

We used a urethane tube and an excised pig carotid as models. The urethane tubes were custom made by an injection process. We used a liquid urethane (Reoflex 20, Smooth-On Inc, Easton, PA) that comes in two different components (A and B), that are mixed in equal amounts. The pig carotid was excised from a pig according to the guidelines from the animal care committee from our institution.

Both the artery and the tube were mounted on a metallic frame and prestretched, the artery to 1.4 times its recoiled length and the tube to 1.24. Both structures were embedded in gelatin (10% by weight) which mimics the properties of surrounding tissue. After the gelatin set the phantom was refrigerated over night and tested the next day.

The day of the experiment, one of the ends of the artery/tube was attached to a column of saline solution in order to vary the transmural pressure while the other end was sealed. 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/tube wall. The localized shear waves were generated using a 3 MHz, 200 µs toneburst with the the confocal transducer, this excitation was repeated at a frequency of 50 Hz to concentrate energy at this frequency as well as harmonics of this frequency up to 2 kHz. The confocal transducer was was at a 30 degree angle with the vertical axis. The propagation of the shear waves was measured with the pulse echo transducer, for this, 21 points separated by 1 mm along the length of the artery/tube were investigated. This transducer was oriented parallel to the vertical axis (orthogonal to the length of the artery). The excitation and measurement were repeated for pressures from 10 to 100 mmHg in 10 mmHg increments. Figure 1 shows a representation of the set up.

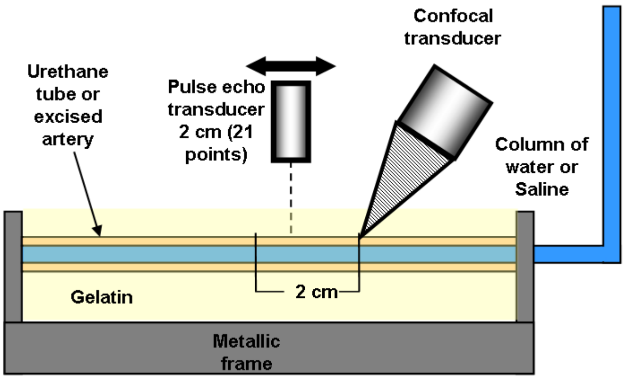

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Figure 1. Representation of the experimental set up for an excised pig carotid. Shear waves were generated using a confocal transducer and the propagation of the wave was measured with an ultrasound pulse echo system.

RESULTS

In Figure 2 is a representative plot of the propagation of the shear waves generated with radiation force on the arterial wall. Only the first of the five excitations is displayed since the frequency analysis was done in this part of the signal. Panel A is for a transmural pressure of 10 mmHg, B for 50 mmHg and C for 100 mmHg. The *x*-axis represents the time of propagation (ms), and the *y*-axis is the distance (in mm) between the confocal transducer and the pulse echo transducer. Note the difference in the slope of the propagating wave as the pressure increases. The data for the tube are not shown since it is similar to the artery data, but there is no change in slopes.

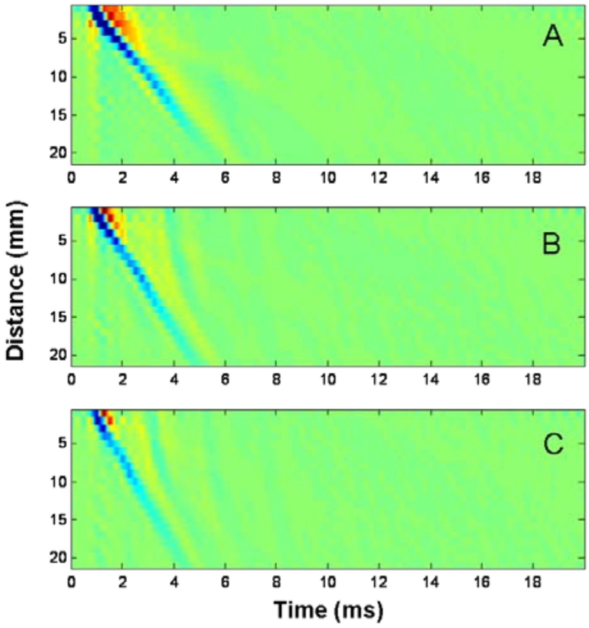

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Figure 2. Propagation of first impulse in the arterial wall at different pressures. Panel A represents the 10 mmHg, B, 50 mmHg and C, 100 mmHg.

Figure 3, shows the k-space (frequency on the *x*-axis and wave number on the *y*-axis) of for the excised artery at 3 different pressures (10, 50 and 100 mmHg, panels A, B and C, respectively). Note how the change in transmural pressure not only changes the slope of the principal mode (change in velocity) but also multiple wave numbers seem to coexist at some frequencies, suggesting the propagation of multiple modes. The k-space for the urethane tube only showed one mode and there were no differences with transmural pressure, therefore the data are not displayed here.

To generate the dispersion curves from the k-space graphs, first an amplitude mask was applied to the k-space, this way the low amplitude noise was discarded. After this the energy peaks for each frequency and wave number were identified. The dispersion curve was constructed using $c = f * 1/\lambda$, where f is the frequency (from 0 to 2 kHz), and λ is 1/wavenumber at which there were energy peaks. Figures 4 and 5 show the dispersion curves for the tube and the artery respectively for the 3 different pressures (10, 50 and 100 mmHg, panels A, B and C).

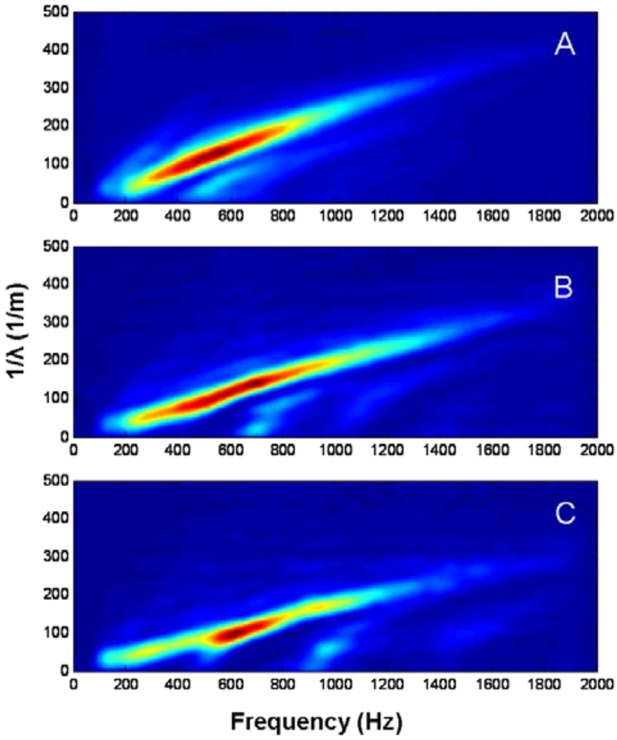

Figure 3. Two dimension FFT representation (k-space) of waves propagating on excised pig carotid artery wall. Panels A, B and C show the results for 10, 50 and 100 mmHg respectively.

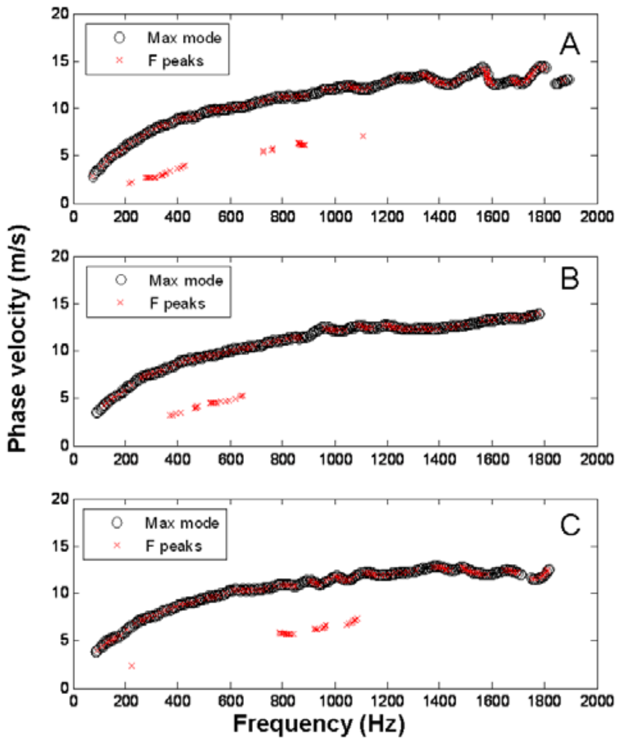

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Figure 4. Dispersion curves for urethane tube. The black circles correspond the to the higher enegy mode. The red x's reporesentd the maximums found for each frequency. Panels A, B and C show the results for 10, 50 and 100 mmHg respectively.

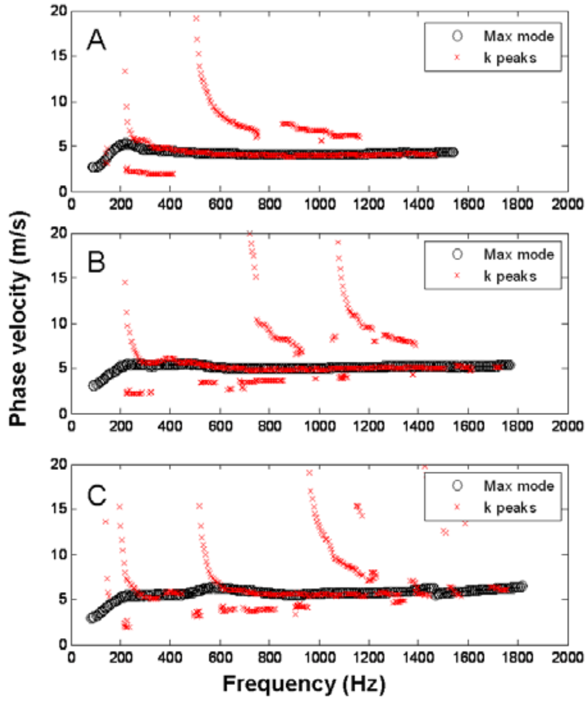

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Figure 5. Dispersion curves for excised artery. The black circles correspond the to the higher enegy mode. The red x's represent the maximums found for each wave number, which allows the better differentiation of the lower energy modes. Panels A, B and C show the results for 10, 50 and 100 mmHg respectively.

DISCUSSION

The propagation of the wave travelling in the artery wall generated by the radiation force was shown in Figure 1. Note how each wave travels the 20 mm in around 5 ms, and how the wave dies out before 20 ms, which is the moment were the second excitation will be generated. This implies that we could potentially generate 50 waves per second and extract elasticity values. This would be more than enough to characterize the arterial properties within the heart cycle. Also, it is important to note how in Figure 2 it is not possible to identify the different propagating modes. Calculation of the group velocity by using cross correlation of the time signal could potentially lead to under or overestimation of material property values. Figure 3 shows the 2D FFT, or k-space, representation of a multimodal propagating wave. Note how in the all the panels (10, 50 and 100 mmHg) aside from the main zero-order anti-symmetric (A0) Lamb-like mode (the strong diagonal segment), higher order modes, and the frequency at which these modes appear, vary with transmural pressur. Changing from 500 Hz for 10 mmHg, to 700 at 50 mmHg and around 900 Hz at 100 mmHg. 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.

It is important to mention that this behavior was not observed in the urethane tubes, and this can be explained by the higher speed of propagation which implies higher stiffness. This will push the higher order modes to the higher frequencies where our signal has very low amplitude and therefore the modes can not be resolved. This can also be appreciated in figure 4, where both the maximum mode and the peaks found at each frequency coincide, meaning that were were no other modes propagating. A different case was shown in Figure 5, where the dispersion curve for the arteries showed multiple modes propagating sumultaneousely at different frequencies. In the signal processing for generating this plot, instead of using the peaks found for each frequency, we looked in the k direction to help to better resolve the modes. Although not shown in this paper due to display difficulties, there is a very clear progression of the modes towards higher frequencies with increasing transmural pressure. This was expected as it has been shown that increasing transmural pressure stiffens the arteries [7, 8] and conventional Lamb wave dispersion curves predict the same type of behavior.

This work shows the use of localized shear waves with high temporal resolution and their potential use in the study of mechanical properties of artery and soft cylindrical structures. This technique could potentially solve some of the limitations that methods like pulse wave velocity have. We also showed how the analysis of this data in the frequency and the wave number domain (by using the 2D FFT) can help identify the different propagating modes, providing a tool that to better characterize the tissue properties. In our studies, the modes seemed to have a Lamb wave-like behavior; therefore future work will be to develop a viscoelastic Lamb wave model for cylindrical structures.

CONCLUSIONS

Clinical availability of arterial elasticity would provide a very important 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 manner. We presented a technique and a modal analysis that has the potential to overcome some of these limitations. Generating localized shar waves using ultrasound radiation force and better characterizing the type of waves generated could potetntially be used to mechanically characterize short segments of the arterial tree to diagnose stiffening of the vasculature before any irreversible changes have occured.

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