Pulse Wave Imaging of Human Abdominal Aortas

In Vivo

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Abstract— Vascular diseases (e.g., abdominal aortic aneurysm or, AAA) lead to changes in the regional aortic wall mechanical properties. Pulse-Wave Imaging (PWI) was previously developed by our group to map the pulse-wave propagation along the abdominal aorta of mice in vivo. In this study, the feasibility of PWI with real-time scanning is shown in human abdominal aortas in vivo. The abdominal aortas of five normal subjects and one AAA subject were scanned. A Sonix RP system (Ultrasonix Medical Corp., Burnaby, Canada) was employed with a phased array at 3.3 MHz. The beam density of the 2-D echograms was reduced to 32 beams in order to obtain a high frame rate of 180-260 Hz. The real-time scanning reduces the artifacts from respiration and transducer motion. The velocities of the aortic wall were estimated using RF-based speckle tracking. The sequences of PWI images visually depicted the propagation of the pulse wave along the aortic wall. The regional pulse-wave velocity (PWV) was measured and used to estimate the Young’s modulus of the aortic wall. In healthy volunteers (n=5), the propagation was relatively uniform, with a correlation coefficient of 0.97 ± 0.01 and a PWV of 3.73 ± 0.19 m/s. The Young’s modulus of the aortic wall was 79 ± 10 kPa. In the aneurysmal aorta, the propagation of the pulse wave was relatively nonuniform with lower correlation coefficients (r=0.65). The PWV and Young’s modulus of the aneurysmal aorta were both found to be higher than in the normal case. The PWI technique was successfully implemented in both normal and aneurysmal human abdominal aortas and shown to provide regional information on the mechanical properties of the aortic wall in vivo.

Keywords—abdominal aortic aneurysm; pulse wave; pulse wave velocity; speckle tracking; Young’s modulus

I. INTRODUCTION

Aortic stiffness has been indicated as an early predictor of cardiovascular mortality, primary coronary events and fatal stroke. The stiffness of the arterial wall is mainly determined by the matrix components of the wall, i.e., the elastin, collagen and smooth-muscle cells [1]. Changes in composition and structure of the wall will alter its stiffness. Various vascular diseases including abdominal aortic aneurysms (AAAs) are known to change the tissue mechanical properties. Noninvasive methods to evaluate the mechanical properties of the AAA wall have been investigated by several groups [2-5].

Pulse-wave velocity (PWV) is typically used for estimating the stiffness of arteries. Pulse waves are flow velocity, pressure and diameter waves generated at the ejection phase of the left ventricle [6]. Their propagation speeds and patterns are related to the vascular mechanical properties (e.g., arterial stiffness). In a straight elastic tube containing a nonviscous liquid, the Young’s modulus of the tube is related to the wave velocity by the Moens-Korteweg equation as follows [6],

\[
c = \sqrt{\frac{E h}{2 R \rho}}
\]

where \(c\) is the wave velocity, \(E\) is the Young’s modulus of the conduit wall, \(h\) is the wall thickness, \(\rho\) is the density of the wall, and \(R\) is the inner radius of the tube.

In Eq. (1), the wall is assumed to be infinitesimally thin that there is no appreciable change in wall thickness. In a wall of finite thickness, the Poisson’s ratio \(\sigma\) must be incorporated. A modified equation is given by [6]

\[
c = \sqrt{\frac{E h}{2 R \rho (1 - \sigma^2)}}
\]

The PWV has been measured through a flow velocity wave, pressure wave or diameter wave. In the conventional foot-to-foot method, the waveforms at the two sites (typically, at the common carotid and femoral arteries) are recorded. The PWV is calculated as the distance between two measurement points divided by the time shift of the waveforms at the two points.

Despite the simple definition of PWV, some problems in the methodology still remain, which limit the interpretation of available findings and the general applicability of the PWV measurement [7]. The foot-to-foot method measures the average PWV between two measurement sites (e.g., at the common carotid and femoral arteries). However, the mechanical properties and geometry are non-uniform along the arteries. In addition, diseases (e.g., AAAs) may alter the mechanical properties regionally. A method with higher spatial resolution is thus needed in order to calculate the regional PWV.

Noninvasive measurement of PWV using ultrasound has recently reemerged of research interest. In order to measure the regional PWV, a high ultrasound frame rate is required. For a given PWV of 4 m/s and an aortic length of 10 cm, it takes only 25 ms for the pulse wave to travel across the entire aorta.
and therefore a frame rate of 40 Hz can capture at most two images of the wave propagation. The higher the frame rate is, the more images are capable to depict the pulse wave, and the more detailed spatio-temporal information on the propagation of pulse wave can be obtained. As a result, in addition to the regional PWV measurement, the propagation of the pulse wave can be imaged, when the high frame rate obtained is high enough.

By using a retrospective ECG gating technique, Pulse-Wave Imaging (PWI) has previously been developed by our group to image the pulse-wave propagation along the aortic wall in mice at a high frame rate of 8 kHz for detection and non-invasive mapping of vascular disease in vivo [7-9].

Similarly, a high-frame rate composite imaging system for high frame-rate and full-view cardiovascular ultrasound imaging was developed [10]. 2-D full long-axis view RF frames with 64 or 128 beams were reconstructed from 5-7 narrow RF sector frames at the high frame rate of 481 Hz. The feasibility of PWV using this system was shown in a healthy volunteer. However, the data acquisition takes 15-21 s, during which the subjects need to hold their breath in order to reduce the respiratory artifacts. This duration of breath-holding may be difficult for some subjects. The motion of the transducer may also affect the quality of the composite image. In the presence of free respiration or transducer motion, PWI may suffer from discontinuity of images between different sectors. In this study, PWV with real-time scanning was developed to avoid the motion artifact.

II. METHODS

A Sonix RP system (Ultrasonix Medical Corp., Burnaby, BC, Canada) was used with a phased array (3.3 MHz). The long-axis view of abdominal aortas of five (5) young normal subjects (age: 29±2 yo) and an AAA subject (age: 70 yo) were scanned. The image depth varied from 6 to 11 cm. The angle of the view is 90°. By reducing the beam density to 32 beams, the frame rate of the ultrasonic images was increased, varying from 180 to 260 Hz depending on the depth. The RF signals were digitized at a sampling frequency of 20 MHz.

The incremental, axial displacements were estimated offline using a one-dimensional (1D) cross-correlation technique on the RF signals. The window size was equal to 3.8 mm with an 80% overlap. The wall velocities were calculated equal to the estimated displacements multiplied by the frame rate.

The estimated wall velocities were color-coded and overlaid onto the 2D grayscale ultrasonic images (i.e., B-mode images). Only the velocities on the anterior aortic wall and the peri-aortic tissue are shown for better visualization, i.e., separation from blood echo noise. The sequence of wall velocity images were generated and formed a ciné-loop. The location of the anterior aortic wall was obtained through manual tracing on the B-mode image. The wall velocity varied with the distance and time of pulse-wave propagation was shown in a 2-D image, indicating the spatio-temporal variation of the pulse-wave propagation.

On the 2-D spatio-temporal images, the foot of the wall velocity pulse was defined as the time-point, at which the velocity attains a value equal to 25% of the peak velocity. The time of the foot was plotted against the distance traveled by the pulse wave. Linear regression was applied on the time-distance plot. The PWV was calculated as the inverse of the linear regression slope, and the correlation coefficient (r) of the linear regression was used to assess the uniformity of the pulse-wave propagation.

The diameter of the aorta was measured from the B-mode images. Because the wall thickness was on the order of the ultrasound resolution, an average value of 2 mm was used in order to avoid dispersion caused by the measurement variance. The Young’s modulus of the aorta was estimated from Eq. (2), by assuming a density of the wall of 1060 kg/m³ and a Poisson’s ratio of 0.45 or, near incompressibility, of the wall.

III. RESULTS

A. Normal Abdominal Aorta

Figure 1 shows the sequence of wall velocity, or PWI, images of the abdominal aorta of a normal subject (#3). Positive and negative velocities denote upward and downward velocities, respectively. The solid arrows indicate the pulse wave front from the proximal (i.e., the right side of the image) to the distal (i.e., the right side of the image) site along the aorta. The figure titles are the time relative to the first data acquired.

![Figure 1. Sequence of the PWI images in a normal aorta](image)

Figure 2 is the spatio-temporal image of the wall velocity in the aorta of the subject. As shown, the pulse wave arrives at the proximal site (e.g., \( x_{PW}=10 \) mm) earlier than at the distal site (e.g., \( x_{PW}=90 \) mm). The dashed lines indicate the delay of the pulse wave occurrence at different regions or, the propagation of the pulse wave. The spatio-temporal variations of the wall velocity in two cardiac cycles are very similar, thus demonstrating the repeatability of PWI.

Figure 3 shows the time of the pulse wave occurrence with respect to the distance traveled by the pulse wave (from the proximal to the distal sites) for the normal aorta. The PWV was estimated equal to 3.87 m/s. The correlation coefficient of the linear regression was 0.97, indicating the uniform propagation of the pulse wave.
Figure 2. Spatio-temporal variation of the wall velocity in the normal aorta. The dashed line indicated the delay of velocities due to pulse wave propagation.

Table I compares the results in the five normal subjects. As shown, the PWV’s in different subjects are similar, with an average of 3.73 m/s. The Young’s moduli are also within the same range, with an average of 79 kPa.

<table>
<thead>
<tr>
<th>Subject</th>
<th>PWV (m/s)</th>
<th>Correlation coefficient (r)</th>
<th>Diameter (mm)</th>
<th>Young’s modulus (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td># 1</td>
<td>3.58</td>
<td>0.96</td>
<td>13.4</td>
<td>68</td>
</tr>
<tr>
<td># 2</td>
<td>3.47</td>
<td>0.99</td>
<td>15.1</td>
<td>72</td>
</tr>
<tr>
<td># 3</td>
<td>3.78</td>
<td>0.96</td>
<td>13.6</td>
<td>77</td>
</tr>
<tr>
<td># 4</td>
<td>3.87</td>
<td>0.97</td>
<td>14.1</td>
<td>83</td>
</tr>
<tr>
<td># 5</td>
<td>3.98</td>
<td>0.99</td>
<td>15.4</td>
<td>97</td>
</tr>
<tr>
<td>Average ± SD</td>
<td>3.73 ± 0.19</td>
<td>0.97 ± 0.01</td>
<td>14.3 ±0.9</td>
<td>79 ± 10</td>
</tr>
</tbody>
</table>

B. Aneurysmal Abdominal Aorta

Figure 4 displays the sequence of the PWI images in the aorta of an AAA subject. Similar to the results in the normal aorta (Fig. 1), the pulse wave travels from the proximal to the distal site of the aneurysmal aorta. On the other hand, the wall velocities are significantly lower in the aneurysmal case (Fig. 4) compared to in the normal case (Fig. 1). Time differs from that in Fig. 3, because it is relative to the first data acquired.

Figure 5 illustrates the spatio-temporal image of the wall velocity in the aneurysmal aorta. As shown, the maximum wall velocities at different locations in the aneurysmal case are lower and are not as uniform as in the normal case (Fig. 2).

Figure 6 shows the time of the pulse wave occurrence as a function of the distance traveled by the pulse wave for the aneurysmal aorta. The time-distance data in Fig 6 are much noisier than the normal case (Fig. 3), as indicated by the lower correlation coefficient (r=0.65) of the linear regression. In this AAA subject, the PWV measured was 4.83 m/s. The aortic diameter was measured equal to 3.6 cm. The Young’s modulus was found to 330 kPa.

IV. DISCUSSION

In this paper, the RF signals of the full field of view of the abdominal aorta were acquired at real time. By reducing the
abdominal aortas in humans are shown
With this technique, regional (<10 cm) pulse wave velocity
reduce the artifacts from respiration and transducer motion when a longer acquisition time is required, e.g., in the ECG gating technique [10].

The AAA is a common but often silent vascular disease. The current clinical criterion for treating AAA’s is an increased diameter above a critical value but does not correlate well with aortic rupture [11], the main cause of death from AAA disease. AAA disease leads to changes in the aortic wall mechanical properties. The preliminary results demonstrate the feasibility of the PWI in both normal and aneurysmal abdominal aorta in vivo. The propagation of the pulse wave along the aneurysmal aorta is not as uniform as in the normal aortas, as indicated by the reduced correlation coefficient (r) of the linear regression. This may be due to the inhomogeneities in aortic wall properties, as suggested by the regional dilation of the aneurysmal region and the underlying histopathological change. The estimated PWV and Young’s modulus of the aneurysmal aorta were found to be higher than those of the normal aortas. Wall velocities in the aneurysmal aorta (Fig. 5) are also found be smaller than the normal aorta (Fig. 1), which may be due to stiffening of the aortic wall. These results were consistent with the increased collagen and decreased elastin in the aneurysmal aorta. In this study, however, data of normal and aneurysmal aortas were acquired from young and old subjects, respectively. Aging also increases the stiffness of the aorta and hence the PWV [6]. Older subjects with and without AAAs will be compared in order to separate the effects of aging in the future.

Ongoing work includes the finite-element modeling of coupling of the aortic wall motion and the flow dynamics (i.e., the fluid-solid interaction) in order to investigate the role of stiffness, geometry and flow patterns in assessing the aortic wall mechanical properties and interpreting the PWI findings with a parametric analysis [12, 13, 14]. In addition, validation of the PWI in estimating the regional PWV and Young’s modulus with phantom experiments should be performed. The inter- and intra-observer variability will also be analyzed in the future in order to demonstrate the reliability and reproducibility of this technique.

V. CONCLUSION

Pulse Wave Imaging (PWI) of both normal and aneurysmal abdominal aortas in humans are shown in vivo. The abdominal aortas were scanned in real time at a frame rate of 180-260 Hz, depending on the imaging depth. The frame rate was deemed sufficient to image the propagation of the pulse wave. The real-time acquisition reduced the artifacts from respiration and transducer motion when a longer acquisition time is required, e.g., in the ECG gating technique [10].

REFERENCES