Artery Research (2015) 11, 19–28

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journal homepage: www.elsevier.com/locate/artres

Performance assessment of pulse wave imaging using conventional ultrasound in canine aortas *ex vivo* and normal human arteries *in vivo*

Ronny X. Li [a], William Qaqish [a], Elisa E. Konofagou [a,b,*]

[a] *Ultrasound and Elasticity Imaging Laboratory, Department of Biomedical Engineering, Columbia University, New York, NY, USA*
[b] *Department of Radiology, Columbia University, New York, NY, USA*

Received 21 May 2015; accepted 11 June 2015
Available online 22 July 2015

KEYWORDS
Abdominal aorta;
Arterial stiffness;
Carotid artery;
Pulse wave;
Pulse wave velocity (PWV);
Pulse wave imaging (PWI);
Speckle tracking;
Ultrasound

Abstract The propagation behavior of the arterial pulse wave may provide valuable diagnostic information for cardiovascular pathology. pulse wave imaging (PWI) is a noninvasive, ultrasound imaging-based technique capable of mapping multiple wall motion waveforms along a short arterial segment over a single cardiac cycle, allowing for the regional pulse wave velocity (PWV) and propagation uniformity to be evaluated. The purpose of this study was to improve the clinical utility of PWI using a conventional ultrasound system. The tradeoff between PWI spatial and temporal resolution was evaluated using an *ex vivo* canine aorta ($n = 2$) setup to assess the effects of varying image acquisition and signal processing parameters on the measurement of the PWV and the pulse wave propagation uniformity r^2. PWI was also performed on the carotid arteries and abdominal aortas of 10 healthy volunteers (24.8 ± 3.3 y.o.) to determine the waveform tracking feature that would yield the most precise PWV measurements and highest r^2 values *in vivo*. The *ex vivo* results indicated that the highest precision for measuring PWVs ~2.5–3.5 m/s was achieved using 24–48 scan lines within a 38 mm image plane width (i.e. 0.63–1.26 lines/mm). The *in vivo* results indicated that tracking the 50% upstroke of the waveform would consistently yield the most precise PWV measurements and minimize the error in the propagation uniformity measurement. Such findings may help establish the optimal image acquisition and signal processing parameters that may improve the reliability of PWI as a clinical measurement tool.

* Corresponding author. 630 West 168th Street, Physicians & Surgeons 19-418, New York, NY 10032, USA. Tel.: +1 212 342 0863; fax: +1 212 342 1648.
E-mail address: ek2191@columbia.edu (E.E. Konofagou).

http://dx.doi.org/10.1016/j.artres.2015.06.001
1872-9312/

Introduction

The arterial pulse wave refers to the pressure and flow velocity waves generated by each contraction of the left ventricle that propagate throughout the arterial tree and induce displacements in the vascular walls, giving rise to the natural pulsation of the arteries.[1,2] One of the most robust and widely used parameters for characterizing arterial mechanical properties is the pulse wave velocity (PWV),[3–5] which is directly and quantitatively related to the Young's modulus of the artery by the well-known Moens–Korteweg equation.[6,7] Thus, the PWV may serve as a surrogate index of arterial stiffness, which has been shown to be directly correlated with cardiovascular risk by numerous clinical longitudinal studies.[8–11]

Pulse ave imaging (PWI) is a noninvasive ultrasound-based technique[12–16] to visualize and map the estimated pulse wave-induced arterial wall displacements in 2D+ time, allowing for assessment of the regional PWV (i.e. across the imaged segment). The advantage of PWI over other image-guided methods for regional PWV measurement[17–21] is that multiple waveforms (i.e. equal to the number of scan lines used) can be acquired along an imaged segment over the same cardiac cycle at high frame rates (up to ∼500 fps *in vivo*[13,15]), providing numerous spatial and temporal samples for local PWV measurement.

A block diagram describing the PWI method in a normal human aorta is shown in Fig. 1. The PWV is estimated as the slope of the linear regression line fitted to the spatio-temporal variation of a characteristic waveform feature (e.g. the 50% upstroke), which also allows the pulse wave propagation uniformity to be assessed as the coefficient of determination r^2. A high r^2 indicates the presence of a dominant PWV equal to the slope of the regression line, suggesting relatively uniform stiffness across the segment. A low r^2 implies that the PWV may be changing throughout the imaged segment due to non-uniform arterial mechanical properties and/or wave reflections. Variance and inconsistency of the PWV and r^2 measurements obtained by PWI may arise due to several imaging and signal processing parameters. In order for PWI to be considered as a reliable

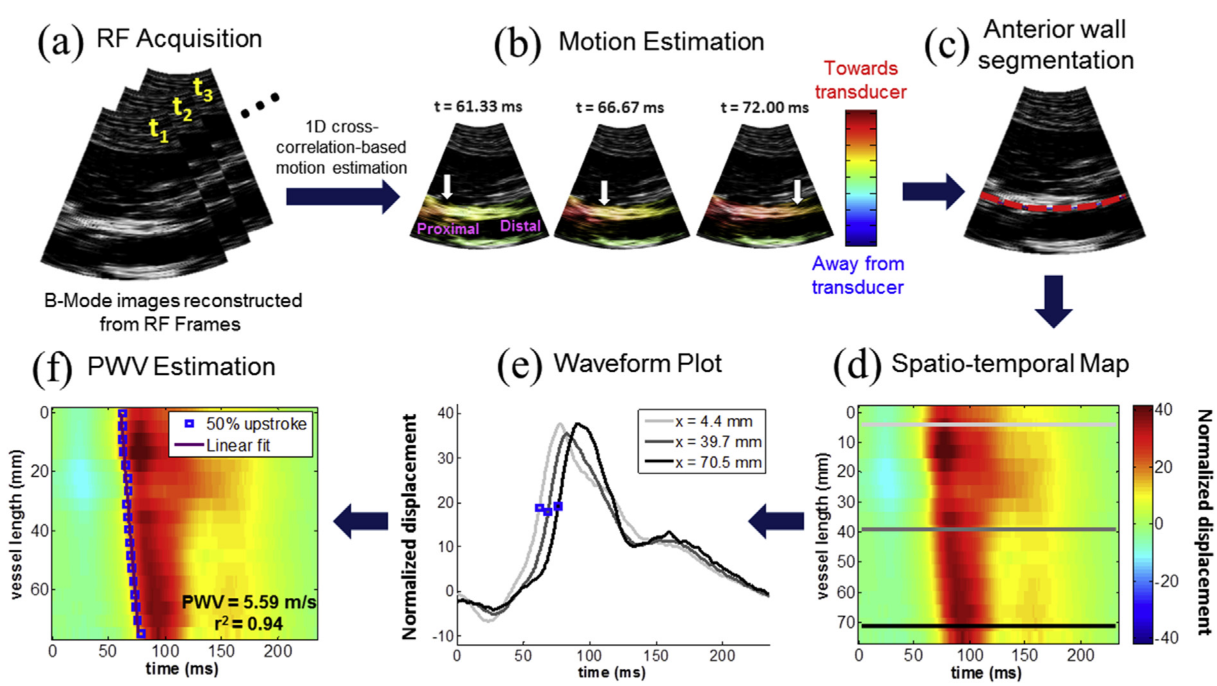

Figure 1 Block diagram of the Pulse Wave Imaging (PWI) method on a normal human aorta *in vivo*. (a) A sequence of RF frames is acquired at the minimum depth required to visualize both walls of the artery of interest. (b) A 1D normalized cross-correlation-based motion estimation method (Luo and Konofagou 2010) is used on the RF signals to compute the inter-frame axial (i.e. parallel to the ultrasound beams) displacements in the arterial walls. The displacement amplitudes are normalized by multiplying by the frame rate. The arrival of the pulse wave induces positive (i.e. towards the transducer) displacements in the anterior wall and negative (i.e. away from the transducer) displacements in the posterior wall. The white arrows indicate the propagation of the wavefront along the anterior wall. (c) The anterior wall is manually segmented (red dotted line) in the first frame of the acquisition sequence, generating a wall trace that specifies the depth of the wall at each scan line (i.e. one value per scan line). This trace is automatically updated in subsequent frames based on the estimated displacements. (d) The wall motion is spatiotemporally mapped by plotting the displacement at each point along the wall trace over time. (e) The normalized displacement waveform at three scan line positions along the anterior wall, corresponding to the light gray, dark gray, and black lines in (d), are shown. The time point corresponding to a characteristic tracking feature (e.g. the 50% upstroke as indicated by the blue dots) is automatically detected in the waveform at each position. (f) Linear regression is performed on the spatio-temporal variation of the characteristic time points along the imaged segment to obtain the slope as the PWV and the coefficient of determination r^2 as an index of propagation uniformity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)