

Assessing the performance of vessel wall tracking algorithms: the importance of the test phantom

K V Ramnarine, B Kanber and R B Panerai

Department of Medical Physics, University Hospitals of Leicester NHS Trust,
Leicester Royal Infirmary, Leicester, LE1 5WW, UK.

E-mail: Kumar.ramnarine@uhl-tr.nhs.uk

There is widespread clinical interest in assessing the mechanical properties of tissues and vessel walls. This study investigated the importance of the test phantom in providing a realistic assessment of clinical wall tracking performance for a variety of ultrasound modalities. B-mode, colour Doppler and Tissue Doppler Imaging (TDI) cine loop images were acquired using a Philips HDI5000 scanner and L12-5 probe. *In-vivo* longitudinal sections of 30 common carotid arteries and *in-vitro* images of pulsatile flow of a blood mimicking fluid through walled and wall-less tissue and vessel mimicking flow phantoms were analysed. Vessel wall tracking performance was assessed for our new probabilistic B-mode algorithm (PROBAL), and 3 different techniques implemented by Philips Medical Systems, based on B-mode edge detection (LDOT), colour Doppler (CVIQ) and TDI (TDIAWM). Precision (standard deviation/mean) of the peak systole dilations for respective PROBAL, LDOT, CVIQ and TDIAWM techniques were: $15.4 \pm 8.4\%$, $23 \pm 12.7\%$, $10 \pm 10\%$ and $10.3 \pm 8.1\%$ for the common carotid arteries; 6.4%, 22%, 11.6% and 34.5% for the wall-less flow phantom, 5.3%, 9.8%, 23.4% and 2.7% for the C-flex walled phantom and 3.9%, 2.6%, 1% and 3.2% for the latex walled phantom. The test phantom design and construction had a significant effect on the measurement of wall tracking performance.

1. Introduction

There is widespread clinical interest in assessing the mechanical properties of tissues and vessel walls as these are important to the onset, diagnosis and treatment of cardiovascular disease. Vessels that have been studied include the common carotid artery, femoral artery, brachial artery, cerebral arteries and the aorta [1]. Recent clinical studies have benefited from ongoing improvements in ultrasound image quality, new imaging techniques and signal processing algorithms. Our own clinical research has focused on the possibility of identifying the vulnerable carotid plaque based on the mechanical wall motion behavior [2].

Various ultrasound techniques have been used to detect and track the vessel wall motion. Computational techniques have been based on analysis of B-mode greyscale images, M-mode, analysis of the raw RF data and various Doppler techniques [3-7]. Tissue Doppler Imaging (TDI) is a relatively new commercial technique that has been optimised to provide images of tissue motion rather than blood flow. The signal processing techniques employed to extract the tissue velocity information

from the RF ultrasound data are typically based on time domain cross-correlation techniques [6] or autocorrelation techniques [8].

This study investigated the importance of the test phantom in providing a realistic assessment of clinical wall tracking performance for a variety of ultrasound modalities and signal processing algorithms. It was hypothesised, that an oscillating vessel wall mimicking material characterised by well defined and high intensity specular reflection from the surface will be more reliably tracked than lower intensity and diffuse/Rayleigh type scattering from a tissue mimicking material. This paper describes work in progress.

2. Methods

2.1. Equipment and data collection

Ultrasound B-mode, colour Doppler and Tissue Doppler Imaging (TDI) cine-loop images were acquired using a Philips HDI5000 scanner and L12-5 probe (Philips Medical Systems). *In-vivo* images of longitudinal sections of 30 common carotid arteries (CCAs) with no ultrasound evidence of disease were obtained by experienced vascular technologists. In accordance with the Helsinki declaration, informed consent and ethical approval for the clinical study was obtained.

The performance of vessel wall tracking algorithms was also assessed using pulsatile flow models incorporating well characterized blood, tissue and vessel mimicking materials in an effort to simulate the *in-vivo* situation. Pulsatile flow (1 cycle/s) of the blood mimicking fluid (BMF) was generated using a computer controlled gear pump. The waveform was selected empirically to approximately simulate the wall motion in the CCA and is similar to a previous study that used a commercial flow phantom [9]. Three flow models were constructed consisting of a 4mm diameter channel through an agar based tissue mimic channel (wall-less TMM phantom), a 4.6mm diameter (0.8mm wall thickness) C-flexTM tube (Cole-Parmer, US) phantom, and a 5mm diameter (1mm thick) custom-made latex tube phantom. The BMF consisted of (%weight): water (83.86%); glycerol (10.06%); dextran (3.36%); 5 micron OrgasolTM (1.82%) and Synperonic NTM surfactant (0.9%). The tissue mimicking material (TMM) consisted of (%weight): water (82.97%); glycerol (11.21%); benzalkoniumchloride (0.46%); 400 grain SiC powder (0.53%); 3 micron Al₂O₃ powder (0.94%); 0.3 micron Al₂O₃ powder (0.88%) and agar 3.00%. The well characterised BMF is described in detail elsewhere [10, 11], as is the agar based TMM [12, 13] and the construction of custom latex tubing [14]. The experimental set-up is shown schematically in Figure 1. Note the outlet tube diameter is constricted to increase the pulse pressure (and consequently vessel wall displacement) in the phantom.

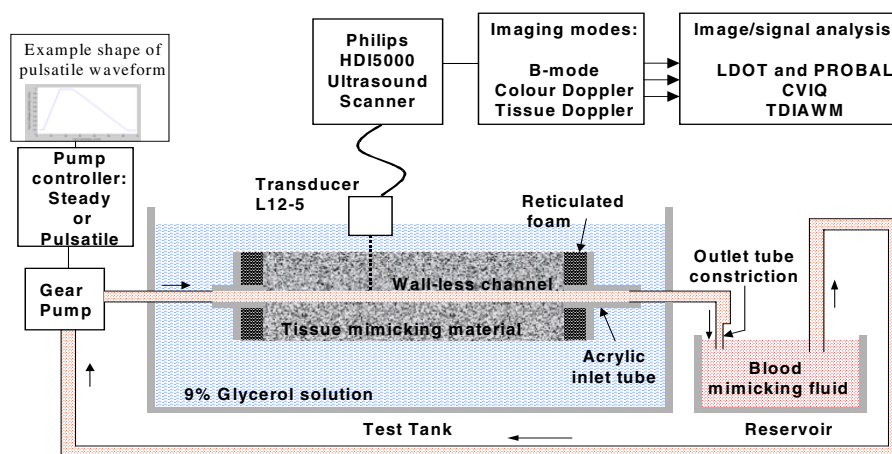


Figure 1. Experimental set-up showing wall-less tissue mimicking material (TMM) flow phantom

2.2. Data analysis

Vessel wall tracking performance was assessed using 3 different techniques implemented by Philips Medical Systems, based on B-mode edge detection (LDOT), colour Doppler (CVIQ) and TDI (TDIAWM). Data were analysed off-line using Philips Research Link HDILAB analysis software and the TDI Arterial Wall Motion proprietary software developed by Philips Research Laboratories [2, 6, 15]. In addition, vessel wall tracking performance was assessed using our new probabilistic B-mode algorithm (PROBAL) [16]. PROBAL is a novel algorithm that was designed to identify and track vessel wall/lumen boundaries in ultrasound images although its potential applications are diverse. Briefly, PROBAL used a data matrix representing the greyscale intensity values to determine the corresponding probability matrix (that a pixel is in the selected vessel lumen) by associating the probabilities of neighbouring points using a semi-Gaussian probabilistic model [16].

The axial wall dilations (defined as the difference between the anterior and posterior wall diameters relative to the reference diastole values) along a longitudinal segment of the artery for each image frame were extracted. Scan line spatial resolution was typically 0.148mm and temporal resolution approximately 30-45Hz. These raw data were exported to MATLABTM for data analysis. The wall dilations at peak systole were temporally averaged over 5 cardiac cycles. Spatial averaging over approximately 1 cm (approximately 70 scan lines) was performed using PROBAL and TDIAWM.

3. Results

Table 1 summarises the results for the peak dilation and % precision as determined using the 4 signal processing algorithms (LDOT, PROBAL, CVIQ and TDIAWM) in the CCA, the wall-less phantom, the C-flex tube and the latex tube phantom. Note that the dilation results between phantoms may be different as the pulsatile flow amplitude and outlet constriction were not standardised and the physical properties (e.g. elasticity and size) were different. However, the dilations measured for each phantom using the 4 algorithms should be the same and correspond to the true (but unknown) dilation.

Table 1. Peak dilation and % precision (standard deviation (SD)/mean) of the spatially and temporally averaged peak systole dilations as determined using LDOT, PROBAL and TDIAWM signal processing algorithms in the common carotid artery (CCA), the wall-less phantom, the C-flex tube and the latex tube phantom.

	CCA ^a	CCA ^b	Wall-less phantom	C-flex vessel phantom	Latex vessel phantom
PROBAL	15.4 ± 8.4%	549 µm 5.9%	87 µm 6.4%	126 µm 5.3%	335 µm 3.9%
TDIAWM	10.3 ± 8.1%	438 µm 2.1%	45 µm 34.5%	175 µm 2.7%	262 µm 3.2%
LDOT	23.0 ± 12.7%	1058 µm 6.9%	117 µm 22.4%	256 µm 9.8%	388 µm 2.6%
CVIQ	10.0 ± 10.0%	1343 µm 7.9%	3570 µm 11.6%	1193 µm 23.4%	6390 µm 1.0%

^aMean ± 1SD of 30 CCA's and ^b example CCA.

Figure 2 illustrates example dilation-time curves for each of the algorithms in the CCA, the wall-less TMM phantom, the C-flex tube phantom and the custom latex phantom.

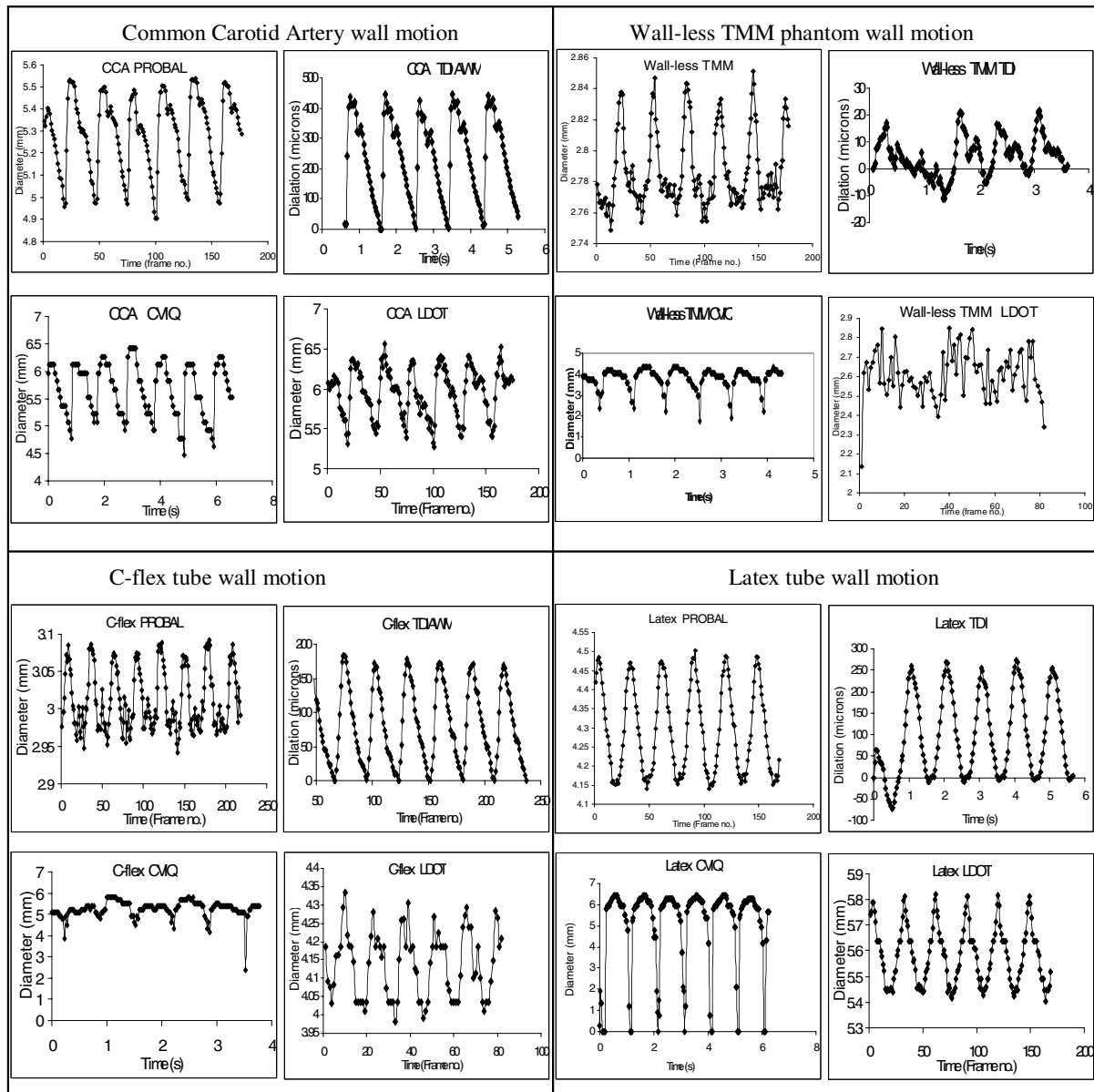


Figure 2. Dilation as a function of time in the common carotid artery (CCA), the wall-less tissue mimicking material (TMM) phantom, the C-flex tube and the custom latex tube as calculated using the 4 signal processing algorithms PROBAL, TDIAM, CVIQ and LDOT.

Figure 3 shows results for the peak dilation in the latex tube as a function of increasing peak pulsatile flow velocity for the LDOT, PROBAL and TDIAM signal processing algorithms. Note that CVIQ data is not shown as this method produced excessively high dilation values.

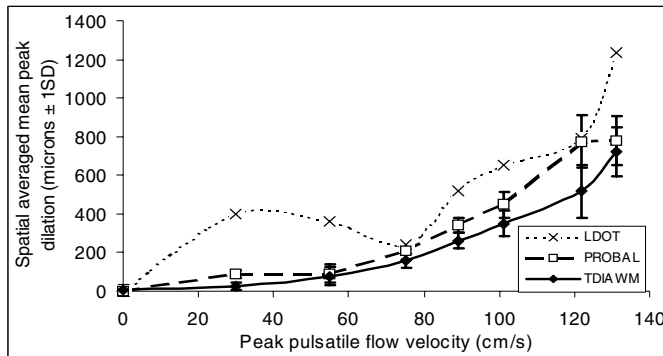


Figure 3. Graph of the spatially averaged mean peak dilation in the latex tube as a function of increasing peak pulsatile flow velocity. Results are shown based on LDOT, PROBAL and TDIAM signal processing algorithms. Error bars indicate $\pm 1SD$ for PROBAL and TDIAM only.

4. Discussion

The results of this study highlight some important considerations for the design and construction of physiologically realistic vessel wall motion test phantoms for the evaluation of ultrasound wall tracking systems. Of particular importance, for the experimental assessment of wall tracking techniques is the target material. The target material gives rise to the ultrasound signal that is identified and tracked. For clinically realistic assessment of performance, it should simulate the characteristics of the *in-vivo* tracked signal- typically from the vessel lumen/wall interface (but not so for LDOT which tracks the anterior adventitia-media interface and the posterior lumen-intima interface). This interface echo is generally easier to identify and track as the low amplitude backscattered signal from blood contrasts with the higher tissue echo from the vessel wall.

The vessel mimicking C-flex and latex tubing produced high intensity specular reflection from the smooth surface. This contrasts with the low intensity, random Rayleigh scattering from the moving BMF, and the diffuse/Rayleigh scattering from the TMM, causing phase aberrations of the backscattered ultrasound. This explains in part, the poor performance of TDIAM using the wall-less phantom, as TDIAM is based on RF cross-correlation signal processing techniques to extract phase shift information, rather than the greyscale signal intensity based method of PROBAL. The lower dilation in the wall-less TMM phantom is a confounding factor although additional experiments (not shown) and the results of Figure 3 substantiated these initial observations. These results demonstrate the need to match important acoustical and physical properties of the test phantom to the actual *in-vivo* characteristics. Although data on these vessel properties are scarce, the *in-vivo* ultrasound/vessel interaction lies between the idealized walled phantom and the wall-less TMM phantom. Other materials such as of polyvinyl alcohol (PVA) cryogel, urethane rubber, alternative agar and gelatin based TMMs may also offer some advantages [13].

In terms of the performance of the 4 algorithms, PROBAL and TDIAM were the most promising techniques. Dilation measurements using CVIQ were grossly inaccurate, mainly caused by loss of colour data within the lumen at diastole due to the wall motion filter. Wall tracking using LDOT was often unreliable and measured inaccurate dilations. Clinical performance was best for TDIAM. As expected, sensitivity to small dilations (tens of microns) was good for TDIAM. Sensitivity using PROBAL was also impressive (Figure 3), despite being based on greyscale image analysis.

The question of what should be measured to characterize wall tracking performance should also be addressed. Measurement of precision may be inappropriate (e.g. LDOT peak systole values may not be normally distributed), and even misleading (e.g. gross measurement inaccuracy using CVIQ not highlighted). A 'gold standard' is thus required.

4.1. Metrological significance

Assessment of new wall tracking techniques requires suitable test phantoms. This study highlights important considerations and limitations in the application of test phantoms for the realistic measurement of clinical wall tracking performance.

5. Conclusion

For realistic assessment of clinical performance, it is important to consider the effect of the quantification methods, the acoustical and physical properties of the test phantoms, interaction with the ultrasound beam, signal processing techniques and vessel wall tracking algorithms. Our results demonstrate how the test phantom design and construction may have a significant effect on the measurement of wall tracking performance.

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