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Experimental validation of non-invasive and fluid density independent methods for the determination of local wave speed and arrival time of reflected wave

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ABSTRACT

The relationship between the vessel diameter (D) and fluid velocity (U) in arteries and flexible tubes has been recently characterized as linear in the absence of wave reflections. This relationship allowed for determining local wave speed (C_{DU}) using the ln*DU*-loop method. Using C_{DU}, it was possible to separate U and D waveforms into their forward and backward components. It was also possible to calculate wave intensity (dI_{DU}), using D and U, from which the arrival time of reflected wave (Trw_{DU}) could be determined. These techniques are fluid density independent and require only non-invasive measurements of D and U.

In this work we experimentally validate the relative accuracy of these new techniques *in vitro*, by comparing their results of C_{DU} and Trw_{DU} to those determined by the established techniques, *PU*-loop and wave intensity analysis, C and Trw, respectively. We generated a single semi-sinusoidal wave in long flexible tubes, and simultaneously measured pressure (P), D, and U at the same site. Sequentially in time, we repeated this experiment at three sites along each of the flexible tubes, which were made of different materials and sizes, and three fluids of different densities.

C_{DU} compared well with that C and likewise Trw_{DU} was very similar to Trw. Varying fluid density did not appreciably change the difference between the results of the two techniques.

We conclude that the new techniques for determining C_{DU} and Trw_{DU}, although independent of density, provide relatively accurate estimates of wave speed and arrival times of reflected waves *in vitro*. The new techniques require only non-invasive measurements of D and U, and further *in vivo* validation is required to establish its advantage in the clinical setting.

1. Introduction

Wave speed (C) is the speed by which disturbance travels along the medium, and it is well accepted as one of the key parameters describing wave propagation in arteries (McDonald, 2007). C depends chiefly upon the local properties of the arterial wall (Bergel, 1961) and widely used clinically to determine arterial stiffness (Asmar et al., 1995). Further, C increases with aging (Mohiaddin et al., 1993) and has been associated with cardiovascular diseases such as atherosclerosis and arteriosclerosis (Blacher et al., 1999).

Several methods have been proposed for the determination of local wave speed. Westerhof et al. (1972) suggested that the ratio of magnitudes of pressure (P) to flow velocity (U), and the characteristic impedance, can be used to determine C. They argued that for the higher harmonics the effect of reflected sinusoidal wave-trains will be negligible, and the characteristic impedance indicates C. Khir et al. (2001a) used the water hammer equation and introduced the PU-loop method for determining C. They argued that in the absence of reflections the relationship between pressure and velocity should be linear and the slope of the initial linear portion of the loop is related to C. To deal with reflections, Davies et al. (2006) introduced the sum of the squares technique for determining C in shorter arterial segments. The application of the above methods requires simultaneous measurements of P and U at the same site. This requirement may not be practical in the clinical setting, due to the invasive nature of collecting reliable pressure measurements.

The arrival time of reflected wave (Trw) to the ascending aorta is another parameter that is of clinical and physiological importance. For example, Trw has been used to diagnose ventricular hypertrophy and cardiac failure (Koh et al., 1998). Earlier arrival of reflected compression waves suggests higher wave speed and causes an increase in P, which is thought to increase left ventricle

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