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Pulse wave propagation in a model human arterial network: Assessment of 1-D visco-elastic simulations against *in vitro* measurements

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ABSTRACT

The accuracy of the nonlinear one-dimensional (1-D) equations of pressure and flow wave propagation in Voigt-type visco-elastic arteries was tested against measurements in a well-defined experimental 1:1 replica of the 37 largest conduit arteries in the human systemic circulation. The parameters required by the numerical algorithm were directly measured in the *in vitro* setup and no data fitting was involved. The inclusion of wall visco-elasticity in the numerical model reduced the underdamped high-frequency oscillations obtained using a purely elastic tube law, especially in peripheral vessels, which was previously reported in this paper [Matthys et al., 2007. Pulse wave propagation in a model human arterial network: Assessment of 1-D numerical simulations against *in vitro* measurements. J. Biomech. 40, 3476–3486]. In comparison to the purely elastic model, visco-elasticity significantly reduced the average relative root-mean-square errors between numerical and experimental waveforms over the 70 locations measured in the *in vitro* model: from 3.0% to 2.5% ($p < 0.012$) for pressure and from 15.7% to 10.8% ($p < 0.002$) for the flow rate. In the frequency domain, average relative errors between numerical and experimental amplitudes from the 5th to the 20th harmonic decreased from 0.7% to 0.5% ($p < 0.107$) for pressure and from 7.0% to 3.3% ($p < 10^{-6}$) for the flow rate. These results provide additional support for the use of 1-D reduced modelling to accurately simulate clinically relevant problems at a reasonable computational cost.

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1. Introduction

Pressure and flow pulse waveforms carry information on the functionality of the cardiovascular system and the morphology of the arterial network, which can be valuable for the diagnosis and treatment of disease. Modelling allows us to study the effect on pulse waveforms of the physical properties of the system, such as arterial geometry and distensibility, cardiac output, heart rate and peripheral impedance to flow, and analyse the mechanisms underlying clinically relevant changes (Stergiopulos et al., 1992; Wang and Parker, 2004; Mynard and Nithiarasu, 2008; Liang et al., 2009). In particular, it allows us to test clinical diagnostic techniques that are based on pulse wave analysis and disentangle their underlying mechanisms (Karamanoglu et al., 1994; Trachet et al., 2010; Alastruey et al., 2006; Alastruey, 2011). These studies can be extremely challenging *in vivo* for technical and physiological reasons; e.g. some vessels are inaccessible, manipulation of the properties of interest can be dangerous or can elicit reflex compensation, and several parameters of interest are not directly measurable.

We have previously shown the ability of the nonlinear 1-D equations of pulse wave propagation in elastic vessels to capture the main features of pressure and flow waveforms measured in well-defined experimental 1:1 replicas of the larger conduit arteries in the human systemic circulation (Segers et al., 1998; Segers and Verdonck, 2000; Alastruey, 2006; Matthys et al., 2007). Matthys et al. (2007) reported average relative root-mean-square errors between numerical and experimental waveforms smaller than 3.5% for pressure and 19% for the flow rate at 70 locations in the tapered silicone network sketched in Fig. 1. Much of these errors arose from relatively high-frequency oscillations in the peripheral vessels predicted in the numerical model but not seen in the experimental measurements. Wall viscosity was suggested

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