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Regressive cross-correlation of pressure signals in the region of stenosis: Insights from particle image velocimetry experimentation

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ABSTRACT

Various anomalies in arterial geometry can cause serious hemodynamic dysfunction. In particular, stenosed arteries can cause reduced blood flow, excess stress on the heart, and elements can shear off causing blockage, which in the brain leads to stroke. This research assesses whether pressure signals obtained close to a stenosis are distinct from signals observed in other areas of the artery.

Particle image velocimetry was used to determine the fluid velocity field within a compliant phantom that mimicked a stenosis in the carotid artery during physiological pulsatile pressure waves. The Navier-Stokes representation of the velocity fields were used to determine the pressure responses across the domain. A three-parameter regressive cross-correlation was used to calibrate the output pressure responses against the pressure input signal.

The transform between the input-output pressure signals allowed detection of the region immediately downstream of the stenosis. In particular, if the cross correlative parameter that relates the instantaneous transfer across the input-output signals was greater than the delayed transfer parameter a stenosis is present. In contrast, the delayed transfer parameter was larger for the region upstream of the stenosis. This outcome is particularly valuable as it does not require calibration of the absolute pressure, which can be difficult to determine physiologically due to factors such as arterial geometry and intrathoracic pressure. However, the outcomes need to be validated in more geometries prior to clinical validation.

1. Introduction

Atherosclerosis is a progressive constriction of the arterial wall (stenosis) by the thickening of the intima and formation of vascular plaque. Atherosclerosis is most serious when it affects the carotid or coronary arteries. In the carotid artery, stenosis can lead to complete occlusion of the artery and is a major cause of stroke and ischemic infarction [1]. In the coronary artery it causes coronary heart disease, which causes 650,000 fatalities per year in the U.S. [2]. Stenosis can produce areas of flow separation and low wall shear stress, which can lead to endothelial dysfunction and to promotion of plaque growth.

There are several published reviews of techniques that can be applied to numerical and experimental studies of the arterial system [3–6]. It is difficult to investigate the interaction between blood flow and the vessel wall *in-vivo*. Vennemann et al. [7] discuss both invasive (laser Doppler velocimetry) and non-invasive (ultrasound particle image velocimetry) techniques. Elkins and Alley [8] provide an in depth review of Magnetic Resonance Velocimetry which utilizes Magnetic Resonance Imaging (MRI) to measure fluid velocity fields. Jamison et al. [9] have investigated the application of an X-ray velocimetry technique. Currently, the resolution of *in-vivo* methods are limited.

In-vitro modelling with artificial flow phantoms allows the fluid mechanics of the circulatory system to be observed directly without the ethical issues associated with *in-vivo* experiments. Extensive work has been performed using both experimental and computational techniques to study rigid models [10–14] representing the arterial system. However, computational fluid mechanics and *in-vitro* experimentation has only recently started to utilise compliant wall geometries [15–24].

Previous investigations have concentrated on investigating the flow field to understand how stenosis affects the velocity distribution [19–21,25,26]. Wall shear stress has also been the focus of many studies as it is a major influence on the structure of the endothelium [27,28]. In the main vasculature, in regions void of arterial geometry change, the arterial vessel diameter changes to maintain a normal physiological wall shear stress (WSS) of approx-

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imately 1–2 Pa [27]. A long-term increase in WSS experienced in an artery results in vasodilation followed by a remodelling of the artery to a larger diameter with the same arterial structure. A low WSS causes a thickening of the intimal layer (producing a stenosis) to re-establish a normal WSS [3]. This information is useful when trying to understand how a stenosis develops, but so far does not help clinical practitioners identify if a stenosis is present

Currently, imaging by MRI scanning is the easiest way to diagnose stenosed arteries. Pressure signals can be obtained more easily and at lower cost than MRI scanning. Clinicians interpret hemodynamic pressure signals from hemodynamic dysfunction patients [29–32]. However, the origin of variance in pressure signals remains ambiguous, and confounds many efforts to standardise care [29,32,33]. Furthermore, interpretation of pressure signals is often restricted to monitoring of pulse pressure and mean venous pressure. Hence, there is scope for qualitative model-based interpretation of pressure signal shapes to lead to improvements in clinical care or diagnosis of anomalous arterial geometry.

This work will determine whether the presence of a stenosis could potentially be captured by qualitative modelling of arterial pressure signals alone. In particular, a velocity field across a compliant axisymmetric stenosis phantom was obtained using particle image velocimetry (PIV). Pressure was obtained from the velocity fields *via* Navier-Stokes analysis and correlated to the upstream pressure signal to ascertain the effect of stenosis.

2. Methods

2.1. Experimental setup

A transparent thin walled compliant flow phantom of an idealised common carotid artery (CCA) with a symmetric stenosis (Fig. 1) was produced with a restriction of 50% by diameter (75% by area) using the investment casting technique presented in Geoghegan et al. [34]. It was constructed at ×3.2-scale using silicone (Dow Corning Sylgard 184 – Young's modulus (E) = 1.32 MPa) with an unstressed internal diameter (D_N) of 20 mm, except at the stenosis, which was 40 mm in length and possessed the two-dimensional coordinates are described by Eq. (1).

$$r^*(z) = \begin{cases} 0.01, & 0.005 > z, or z > 0.045 \\ 0.0075 + 0.0025 \cos\left(\frac{\pi}{0.02}(z - 0.005)\right), & 0.005 \le z \le 0.045 \end{cases} \quad (1)$$

where r^* is the unstressed radius to the internal surface of the phantom wall [m] and z is the axial position beginning 5 mm before the stenosis [m].

The phantom had an unstenosed wall thickness (h) of 1.28 ± 0.05 mm, which was selected to ensure that distensibility (d)

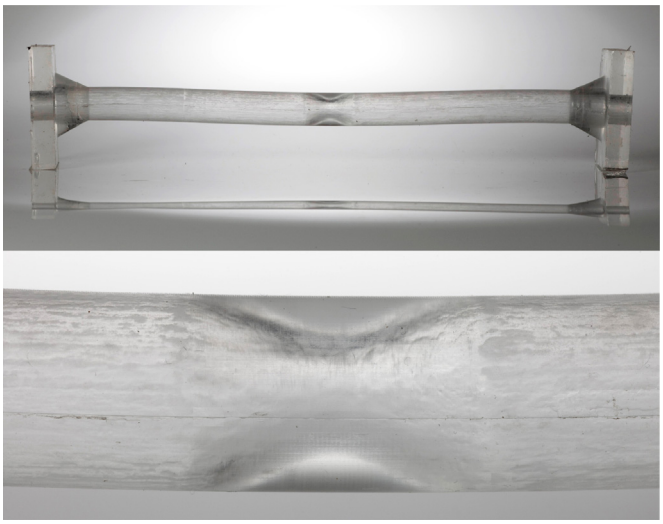

Fig. 1. (Above) Silicone flow phantom representing the common carotid artery with symmetric stenosis. (Below) Magnification of the flow phantom with a 50% symmetric stenosis.

in the phantom (*in-vitro*) was equivalent to the human CCA (*in-vivo*) (Eq. (2)) [35].

$$d = \frac{D}{Eh} \rightarrow h_p = \frac{D_{N,P} E_{IV} h_{IV}}{D_{N,IV} E_P} \quad (2)$$

where E is the elastic modulus, the subscript P denotes the phantom and the subscript IV represents *in vivo* conditions. Full justification of the biomimicry as well as the manufacturing methodology used to generate the phantom can be found in Geoghegan et al. [20,34]. A schematic of the flow circuit used is shown in Fig. 2. The working fluid was an aqueous glycerine solution of 39:61 ratio by weight, which provided a refractive index that matched the silicone phantom (n = 1.141) [34]. The fluid had a viscosity (ν) of 10.2×10^{-6} m^2 s^{-1} and a density (ρ) of 1150 kg m^{-3} at 20 °C. The fluid was seeded with density-matched 10 μm hollow silver coated glass spherical particles. The compliant phantom was placed in an external pressurisation chamber (Fig. 2(g)) that contained a water/glycerol mixture identical to that used in the flow circuit but without the particles. The pressure within the phantom was set above the pressure sustained in the compression chamber to avoid phantom wall collapse. A physiological flow wave was produced by means of a piston pump driven by a stepper motor attached to a ball screw (Fig. 2(a)). An in-house National Instruments LabVIEW code controlled the piston system with an electromagnetic flow meter

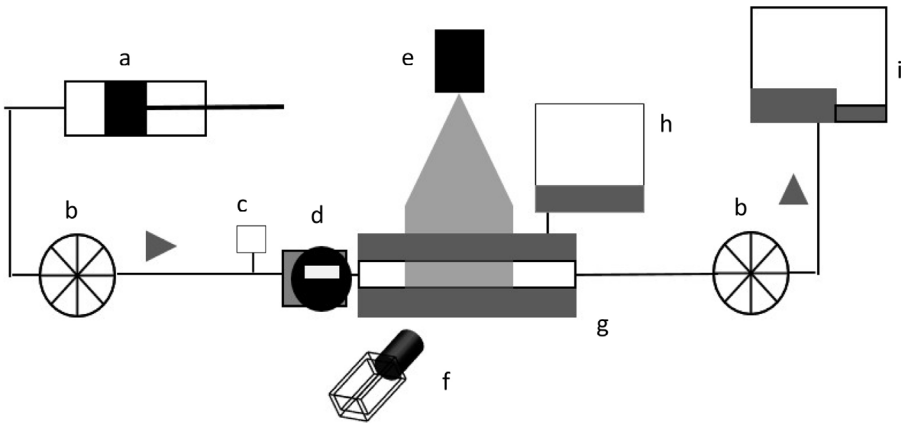

Fig. 2. Schematic view of the experimental setup (a) piston pump (b) flow straightener (c) pressure transducer (d) electromagnetic flow meter (e) laser and optics (f) camera (g) flow phantom inside external bath (h) pressure control tank (i) exit tank with weir.

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