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Insights on arterial secondary flow structures and vortex dynamics gained using the MRV technique

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ABSTRACT

The purpose of this study was to gain an understanding of the formation of arterial secondary flow structures due to physiological parameters such as geometry (curvature), pulsatility and harmonics of inflow conditions. The variation of the unsteady pressure gradient, inflow vorticity and wall shear stress, and its concomitant effect on the secondary flow morphology during the pulsatile flow cycle was investigated. *In vitro* experimental investigation of arterial secondary flow structures was performed using the magnetic resonance velocimetry (MRV) technique in a 180° curved artery model at Stanford University. MRV benefits include its being a tracer-particle-free technique and its ability to resolve a full, three-dimensional flow field. In this paper, we discuss the kinematics of vorticity in the following two regions of a 180° curved artery model; (i) the entrance- (or straight-inlet pipe) and (ii) the 180° curved pipe-region. We applied the Womersley solution in the entrance-region to ascertain the time-dependent pressure drop per unit length, in-plane vorticity and wall shear stress for a pulsatile, carotid artery-based flow rate waveform. We hypothesize that in the 180° curved pipe region, the time rate of change of circulation will discern the propensity of large-scale, deformed Dean-type vortices to separate into two vortices in pulsatile arterial flows.

1. Introduction

Arterial geometries in the human vasculature are intrinsically curved and blood flow is predominantly pulsatile. It is well-documented that flows in curved conduits are subjected to a combination of curvature-induced centrifugal forces and adverse pressure gradients leading secondary flow motion. In planar cross-sections of such curved vessels, vortical patterns appear as projections of the secondary flow motion. These secondary flows are known by their clinical parlance as 'spiral blood flow' structures. They are known to influence wall shear stress and exposure time of blood-borne particles that are closely related to the cardiovascular disease known as atherosclerosis. The study presented in this paper is motivated by the clinical implications of spiral blood flow patterns, wherein hemodynamics and coherent motions of vortices could potentially impact the overall cardiovascular health.

Early experimental investigations of the problem of steady flows in curved pipes were performed by Eustice (1910) before Dean (1927a, 1927b, 1928) conducted seminal analytical studies. Dean (1927a, 1927b, 1928) used power series expansions of axial velocity and stream function incorporating two parameters viz., curvature ratio ($\delta = r/R$) and curvature-related Reynolds number that came to be known as the Dean number ($K = \sqrt{2\delta}\,Re$). An analytical expression for secondary flows under steady inflows in pipes of fixed curvature was presented. The main conclusion was that the flow rate in curved pipes under laminar, steady flow conditions depends on the Dean number (K). While the streamwise pressure gradient, p_ℓ is maintained, the flow rate is reduced due to the combined effects of geometry (δ) and secondary steady flows. Lyne (1971) and Waters and Pedley (1999) among several others have analyzed oscillatory flows in curvatures. One important outcome of their work is the characterization of a two-vortex system in the inviscid core regions of the flow, that has been referred as the Lyne vortex system in the literature. Lyne (1971) used two matched asymptotic expansions; one near-wall and other in the interior and demonstrated that the secondary flows consist of a four-vortex system. Secondary flow structures in the interior regions of the pipe rotate in the opposite direction to those (Dean vortices) that form under steady pressure gradients.

1.1. *Role of flow rate deceleration phase in pulsatile blood flows*

Previous publications by Bulusu and Plesniak have discussed the formation of multi-scale secondary flow structure morphologies under pulsatile flow rate conditions (Glenn et al., 2012; Bulusu and Plesniak, 2013; 2015; Bulusu et al., 2014; van Wyk et al., 2015; Plesniak and

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Bulusu, 2016). Sudo et al. (1992) classified secondary flows into five patterns that included transitional features such as deformed Dean-, intermediate Dean-, Lyne-type vortices and an additional pair of twin vortices by varying the Womersley numbers, $\alpha = 5.5–28$ and oscillatory Dean numbers, $K = 40–500$. The (square of the) Womersley number defined as the ratio of transient inertia forces ($\rho\omega u$) and viscous forces ($\mu u/r^2$) (Womersley, 1955). Previous experiments on secondary flow structure morphologies in a 180° curved artery model have discussed the formation of multi-scale secondary flow structure morphologies under pulsatile flow rate conditions and shown a dependence on pulsatility and harmonics of inflow conditions, especially during deceleration phases (Glenn et al., 2012; Bulusu and Plesniak, 2013; 2015; Bulusu et al., 2014; Plesniak and Bulusu, 2016). Boiron et al. (2007) investigated the dependence of the secondary flow patterns on several systolic flow rate waveforms and observed transitional secondary flow structures during the deceleration phases at the 90° plane of the curved pipe model. Timité et al. (2010) also investigated the effects of pulsatility and stated that during the deceleration phase, under the effect of reverse flow, the secondary flow intensity increases with the appearance of Lyne-type secondary flow structures. Krishna et al. (2017) state that a deceleration phase corresponds to the flow reversal at the inner curvature of the curved conduit. Deceleration, however, is not required for separation from the inner curvatures that correspond to the large-scale morphological changes in the secondary flow structures.

1.2. Research questions and organization of the paper

From the brief review of the literature it is learned that flow in curved conduits representative of blood flows encompass a wide range of hydrodynamic and geometrical parameters. The following are two of the several the resulting research questions that are being discussed in this study:

(i) What is the variation of unsteady pressure gradient, vorticity and wall shear stress encountered during pulsatile inflow?
(ii) What is its concomitant effect on the secondary flow morphology during the pulsatile flow cycle?

The magnetic resonance velocimetry (MRV) technique developed at Stanford University by researchers Dr. Christopher Elkins and Prof. John K. Eaton was used in addressing the aforementioned research questions that are critical toward formulating a three-dimensional, experimental flow visualization of arterial secondary flows.

The paper is organized in the following manner. In Section 2, the scope of the paper is described with the flow regimes found in arterial flows and the main contribution of this study. In Section 2.1, the physiological significance of the 180° curved artery is established and in Section 2.2, the inflow conditions are explained and the reason for time period scaling is provided. Section 3 provides a description of the MRV experimental set up in Stanford University followed by Section 3.1, wherein the blood analog fluid and its composition is explained. In Section 4, the methodology followed in the analyses of inflow conditions in the entrance region and the circulation estimation in the 180° curved pipe region is presented. The results of Fourier analysis of the flow rate waveform, inflow vorticity and wall shear stress are presented in the results-section (Section 5). The time rate of change of vortex-circulation as a potential descriptor of the splitting of arterial secondary flow vortices is also discussed in this section. This is followed by the conclusions-section (Section 6).

2. Scope of the current study

The phenomena presented in this paper are characterized by Eq. (1) that relates the dimensionless pressure gradient in the streamwise direction (p_ℓ) in a tube with uniform curvature. In Eq. (1), G is a superimposed mean pressure gradient in the otherwise (zero-mean) oscillatory pressure gradient, V is a dimensionless velocity amplitude and α is the Womersley number (Pedley, 1980).

$$-p_\ell = G + \alpha^2 V \cos \alpha^2 t \tag{1}$$

Eq. (1)can be used to interpret and classify flows in curved pipes into the following viscous, laminar flow categories:

(i) *Steady flow*: $G = constant$, $\alpha = 0$ (See references by Eustice, 1910; Dean, 1927a; Dean, 1927b; Dean, 1928; Ault et al., 2015)
(ii) *Oscillatory flow*: $G = 0$, $0 < \alpha < \infty$ (See references by Lyne, 1971; Sudo et al., 1992; Waters and Pedley, 1999; Krishna et al., 2017)
(iii) *Pulsatile flow*: $G > 0$, $\alpha > 0$ (See references by Hamakiotes and Berger, 1988; Siggers and Walters, 2008)

In the study presented in this paper, we investigated the spiral motion of the blood with flow pulsatility found in the systemic circulation of the cardiovasculature. We used a rigid, model-artery to understand the flow behavior of a Newtonian, blood-mimicking fluid. A combination of the following two well-defined geometries was used to embody curvatures in blood vessels, found ubiquitously in the human vasculature (See Fig. 1):

(i) *Upstream-cylindrical pipe*: This pipe represents the entrance region of the experimental set up where the unsteady pressure gradient, inflow vorticity and wall shear stress were analyzed with respect to the harmonics of inflow pulsatility (See Fig. 2).
(ii) 180° *degree curved, U-bent pipe with curvature ratio (δ),* 1/7: This pipe represents the curved region of the experimental setup where secondary flows persist. In this region, the vortex decay-related phenomena such as splitting were addressed by examining the material rate of change of circulation in a viscous blood analog fluid.

Bulusu and Plesniak (2013, 2015) discussed the spatio-temporal, evolution of the large-scale vortical structures associated with secondary flows, i.e. deformed Dean-, Lyne- and Wall-type (D-L-W) vortices in a 180° curved artery model. The D- and W-type vortices have been observed to emerge from the same system of vortex tubes generated close to the inlet of the curved artery model that later bifurcate into two separate vortical patterns as discussed in a paper by Plesniak and Bulusu (2016). The results presented in the previous publication by Plesniak and Bulusu (2016) discussed the preliminary findings of the magnetic resonance velocimetry (MRV) experiments conducted at Stanford University.

In this study we discuss the results from MRV-data with theoretical considerations and the role of kinematics of vorticity in the formation of arterial secondary flows. Particularly, the rate of change of circulation of deformed Dean-type (D) vortices were discussed with a visualization of the vortex-line and the ensuing material volume discussion. We hypothesize the rate of change of circulation as a measure of splitting and breakup of the large-scale, Dean-type vortices as one of the main contributions of this study. The novelty of this study resides in the combination of the analysis and the implementation of the MRV technique to understand the physics of arterial secondary flow structures under pulsatile flow conditions. The dynamics of these vortices have a bearing on the distribution of shear stress and blood-borne particle residence times leading to cardiovascular diseases such as atherosclerosis.

2.1. Physiological significance of the 180° curved artery model geometry with curvature ratio (δ), 1/7

A carotid artery-based flow rate waveform is used in the MRV experiments presented in this study. The geometry of the test section is a combination of an *upstream-cylindrical pipe* and a 180° *degree curved, U-bent pipe with curvature ratio (δ),* 1/7 as mentioned in Section 2. The