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Secondary flow structures under stent-induced perturbations for cardiovascular flow in a curved artery model

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ABSTRACT

Secondary flows within curved arteries with unsteady forcing result from amplified centrifugal instabilities and are expected to be driven by the rapid accelerations and decelerations inherent in physiological waveforms. These secondary flows may also affect the function of curved arteries through pro-atherogenic wall shear stresses, platelet residence time and other vascular response mechanisms.

Planar PIV measurements were performed under multi-harmonic non-zero-mean and physiological carotid artery waveforms at various locations in a rigid bent-pipe curved artery model. Results revealed symmetric counter-rotating vortex pairs that developed during the acceleration phases of both multi-harmonic and physiological waveforms. An idealized stent model was placed upstream of the bend, which initiated flow perturbations under physiological inflow conditions. Changes in the secondary flow structures were observed during the systolic deceleration phase ($t/T \approx 0.20$–0.50). Proper Orthogonal Decomposition (POD) analysis of the flow morphologies under unsteady conditions indicated similarities in the coherent secondary-flow structures and correlation with phase-averaged velocity fields.

A regime map was created that characterizes the kaleidoscope of vortical secondary flows with multiple vortex pairs and interesting secondary flow morphologies. This regime map in the curved artery model was created by plotting the secondary Reynolds number against another dimensionless acceleration-based parameter marking numbered regions of vortex pairs.

1. Introduction

Arterial fluid dynamics is highly complex; involving pulsatile flow in elastic tapered tubes with many curves and branches. Flow is typically laminar, although more complicated flow regimes can be produced in the vasculature by the complex geometry and inherent forcing functions, as well as changes due to disease. Strong evidence linking cellular biochemical response to mechanical factors such as shear stress on the endothelial cells lining the arterial wall has received considerable interest (Berger and Jou, 2000; Barakat and Lieu, 2003; White and Frangos, 2007; Melchior and Frangos, 2010). Secondary flow structures may affect the wall shear stress in arteries, which is known to be closely related to atherogenesis (Mallubhotla et al., 2001; Evegren et al., 2010). Wall shear stress, especially low and oscillating wall shear stress has been shown to be important in arterial disease (Mallubhotla et al., 2001; Weyrich et al., 2002).

1.1. Steady inflow conditions

In curved tubes, secondary flow structures characterized by counter-rotating vortex pairs (Dean vortices) are well understood to result from amplified centrifugal instabilities under steady flow conditions. In a fundamental sense, secondary flows are important because they may significantly alter boundary layer structure (Ligrani and Niver, 1988). Standard Dean vortices manifest as a pair of counter-rotating eddies with fluid moving outwards from the center of the tube, away from the radius of curvature of the bend and circulating back along the walls of the tube (Dean and Hurst, 1927; Dean, 1928). Daskopoulos and Lenhoff, (1989) addressed the issue of stability of Dean vortices by stating that the Navier–Stokes equations for sufficiently small Dean numbers have a unique, unconditionally stable (primary) solution, while bifurcations may occur at higher Dean numbers. The bifurcation of two-vortex (primary) solution into a four-vortex solution for ducts of circular cross-section appeared to occur at Dean number 960 (Daskopoulos and Lenhoff 1989). Effects of flow rate, geometry, and the ratio of the tube radius to that of curvature on the stability of Dean vortices were reported by Mallubhotla et al. (2001). Twisting and bifurcation of vortices increased with increasing flow rate and radius ratio, and

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the observation of a six-vortex pattern was discussed (Mallubhotla et al., 2001; Belfort et al., 2001). Belfort et al. (2001) also found that the behavior of vortices in the secondary flow, specifically the twisting and bifurcating of vortices, affects the wall shear stress. Vascular response mechanisms can be initiated by changes in the wall shear stress should these large-scale structures persist.

1.2. Unsteady inflow conditions

Under unsteady, zero-mean, harmonic, oscillating conditions, flow in the same bend results in the confinement of viscous effects to a thin region near the wall (Stokes' layer) and exhibits entirely different secondary flow patterns. When the radius of the tube is large compared with the Stokes' layer thickness, vortical structures in the Stokes' layer rotate in the same directional sense as the Dean vortices in the steady flow case. This rotation drives the fluid in the core to generate the inward-centrifuging Lyne vortices (Lyne, 1970). For flow forced in a zero-mean sinusoidal mode, Lyne's perturbation analysis (with Stokes' layer thickness as the perturbation parameter) predicted that inward centrifuging occurs at Womersley numbers greater than 12. In curved tubes with sufficiently high unsteady forcing frequency, secondary flow development is dominated by the near-wall viscous Stokes' layer (Lyne, 1970). The formation of secondary flow structures has been shown to be influenced by the centrifugal force and the radial pressure gradient (Boiron et al., 2007). Timité et al. (2010) stated that pulsatile flow could produce more complicated secondary flows. They observed that in a 90° circular elbow, the intensity of the secondary flow decreased during the acceleration phase and in the deceleration phase under the effect of reverse flow, the secondary flow intensity increased with the appearance of Lyne-type flow structures.

Regime maps of secondary flow structures depict the changing flow morphologies under certain dimensionless parameters. Under steady inflow conditions these regime maps present regions of bifurcations, variations in vortical scales and counts. A regime map to characterize Dean vortices was created for steady inflow conditions and Dean numbers up to 220, and later extended to 430 by Ligrani and Niver (1988) and Ligrani (1994). Transition of a two-vortex Dean-type system into a bifurcating four-vortex Dean-type system is described by Mallubhotla et al. (2001) in another domain map. Development of secondary flows within a curved bend with unsteady forcing is expected to be driven by the rapid accelerations and decelerations inherent in such waveforms. A regime map was also developed by Sudo et al. (1992) to classify secondary flow under oscillatory conditions into five distinct patterns. For pulsatile flow conditions flow regime maps were created in related bioengineering applications, *e.g.*, classification of flow patterns in a centrifugal blood pump (Shu et al., 2008, 2009). Their research emphasized the importance of pulsatility in curved tubes and the associated time derivative of the flow rate (dQ/dt) on hemodynamics within clinical scale Turbodynamic Blood Pumps (TBPs). A regime map was developed for the ensuing pulsatile flow conditions that provided a preclinical validation of TBPs intended for use as ventricular assist devices.

The observed correlation between vascular response and mechanical stimuli has been the impetus for many fluid mechanics investigations of geometries known to be pathological or pro-atherogenic, such as stenoses (Ahmed and Giddens, 1983; Berger and Jou, 2000; Peterson, 2006). Consequently, it is necessary to investigate secondary flows in a bend subjected to unsteady non-zero-mean flow forcing that will be relevant to cardiovascular flows. The importance of the ongoing research program presented in this paper is the creation of a regime map that characterizes secondary flows based on the forcing flow waveform alone. Flow waveforms are easier to measure than velocity fields. Clinical implications of such studies include characterization of secondary flow morphologies based on patient-specific flow waveforms.

The main objective of the study presented in this paper is to characterize the secondary flow morphologies based on the non-dimensional parameters which characterize the driving waveform. One such parameter that is considered is the Dean number that relates centrifugal forces to viscous forces and is given by the following equation:

$$D = \frac{2Ua}{v}\left(\frac{a}{R}\right)^{1/2} \tag{1}$$

where U is the centerline velocity (measured upstream of the bend) in the primary flow direction, a is the pipe inner radius, v is the kinematic viscosity of the fluid, and R is the radius of curvature.

2. Experimental facility

A schematic diagram of the experimental facility is shown in Fig. 1. A test section was specially designed to enable 2-D Particle Image Velocimetry (PIV) measurements of secondary flow at five locations within the bend with minimal optical distortion. The test section consisted of an 180° bend formed from two machined acrylic pieces. Pipes of 12.7 mm inner diameter were attached to both the inlet and outlet of the test section with lengths of 1.2 m and 1 m, respectively, to ensure that fully developed-flow entered the test section. A stent model could be installed between the test section and the inlet pipe. Experiments were conducted with an idealized stent model (Fig. 2) to observe the effects of perturbations on the secondary flow characteristics. The 88.9 mm (3.5 in) long idealized stent model consisted of an array of 13 equi-spaced O-rings of 1/16 in (1.58 mm) cross-sectional diameter that protruded into the flow (by half of the O-ring cross-sectional diameter, 0.79 mm). A programmable gear pump (Ismatec model BVP-Z) was used to drive the flow.

The voltage waveform generated to control the pump speed was supplied by a data acquisition card (National Instruments DAQ Card-6024E) using a custom virtual instrument written in LabView. A trigger signal for the PIV system was generated by the same data acquisition module to synchronize measurements. A refractive index matching fluid was used in the experiments to minimize optical distortion of the particle image. The fluid was composed of 79% saturated aqueous sodium iodide, 20% pure glycerol, and 1% water by volume with a refractive index of 1.49 at 25 °C (77 °F). The fluid kinematic viscosity was 3.55 cSt (3.55×10^{-6} m^2/s), which closely matches that of blood. To eliminate glare from the boundaries, spherical fluorescent particles with mean diameter of 7 μm were used to seed the fluid for PIV measurements and imaged through a narrow band-pass optical filter installed on the camera. The seeding particles had a density of 1.05 kg/cm^3.

2.1. Driving waveforms

Peterson and Plesniak (2008) found that the secondary flow patterns in the circular bend strongly depend on the forcing flow waveform. The physiological flow waveform used in this study is based on ultrasound and ECG measurements of blood flow made by Holdsworth et al. (1999) within the left and right carotid arteries of 17 healthy human volunteers. The physiological waveform is characterized by increased volumetric flow during the systolic phase when the blood is ejected from the heart. The dicrotic notch, which reflects the cessation of systole, occurs at the minimum volumetric flow and is followed by the diastolic phase (Fig. 3). The period of the waveform was 4 s, which is scaled based on physiological Womersley number (α) of 4.2. Thus, the geometry, flow