Secondary Flow Measurements in Models of Curved Arteries

Autumn L. Glenn, Fangjun Shu and Michael W. Plesniak

Department of Mechanical and Aerospace Engineering

THE GEORGE WASHINGTON UNIVERSITY WASHINGTON DC

INTRODUCTION

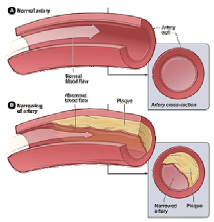

Fig I.1: Normal artery and a narrow artery due to atherosclerosis [1]

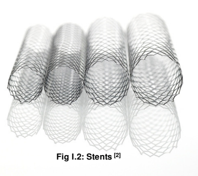

Fig I.2: Stents [2]

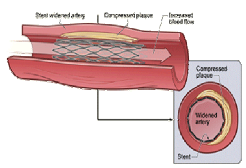

Fig I.3: Stent in artery [3]

- The most prevalent cardiovascular disease is atherosclerosis, the occlusion of the artery due to the buildup of fatty materials on the artery wall.
  - Stent implantation has been proven to be an effective treatment, which provides a mechanical means to increase the diameter of the lumen in a stenosed artery in order to restore normal blood flow rates.
  - 20 – 40% of bare metal stent recipients experience a restenosis (regrowth of the stenosis) within 6 months.
- The correlation between progression of atherosclerosis and hemodynamic phenomena, such as wall shear stress (magnitude and gradients), is well-recognized.
- Influences of secondary flows on atherosclerosis are not well studied, even though they are common in blood vessels due to the complex geometry of the vasculature and the pulsatile nature of blood flow.
  - Steady flow through a curved pipe exhibits Dean vortices
  - Oscillatory flow can exhibit Lyne vortices within the cross-section of the bend
- Understanding of the flow in arteries and near stents will lead to better understanding the mechanism of restenosis and improved stent design.

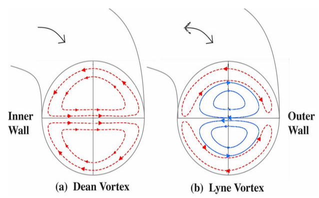

Fig I.4: Secondary flow structures in (a) steady and (b) zero-mean harmonic flow

EXPERIMENTAL SETUP / METHODS

- In-vitro investigation of secondary flow vortices within a 180º circular bend, under pulsatile flow conditions was conducted using a 2-D Particle Image Velocimetry (PIV) system.
  - Experiments are performed in a 180º acrylic bend with a curvature ratio of 1/7. Straight pipes are attached at either end of the bend to ensure fully developed flow.
  - The working fluid has the same optical refractive index as acrylic to minimize optical distortion.
  - Model does not account for compliance or elasticity of healthy arterial vessels.

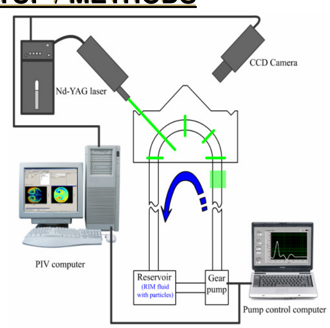

Fig E.1: Experimental Setup

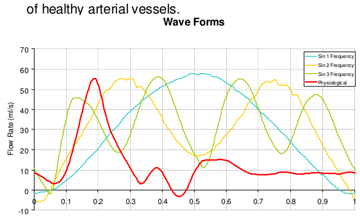

Fig E.2: Plot of Waveforms Used

- Four different waveforms were tested.
  - The physiological waveform is based on measurements in the human carotid artery[4].
  - Three non-physiological waveforms with combinations of harmonic components with difference frequencies were used to perform parametric analysis

RESULTS

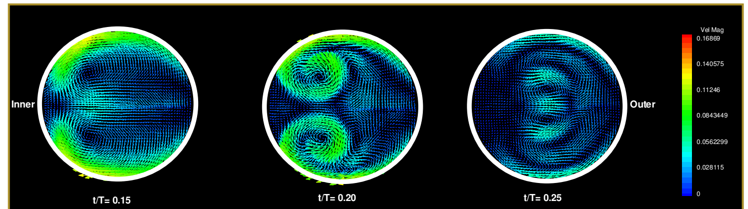

Fig R.1: The development of vortices in the secondary flow (physiological wave form)

- Data were acquired at 0º, 45º, 90º, 135º and 180º locations. Only the results at 90º were presented for brevity.
- Dean vortices were observed to move inward during flow acceleration and to the outside during flow deceleration. They eventually break down during late systole.
- Lyne vortices were initiated before peak systole and persisted throughout systole
- To predict flow characteristics for patients with different cardiac waveforms, a parametric study was conducted.
- Two non-dimensional parameters were used to characterize these streamwise vortices.

$$\text{Dean Number} = \frac{UD}{\nu}\sqrt{\frac{a}{R}}$$

$$\dot{D} = \frac{dU}{dt}\frac{DT}{\nu}\sqrt{\frac{a}{R}}$$

- During flow acceleration (**Region I**), evolution of streamwise vortices is dependent on the input flow rate, as well as the velocity profile. Hence there were no well defined patterns.
- During flow deceleration, the pattern of vortex pairs was better defined. **Regions III and IV** correspond to flows with 2 and 3 vortex pairs, respectively.
- Additionally, regimes with low flow rate (**Region II**) were observed to contain Dean vortex pairs.

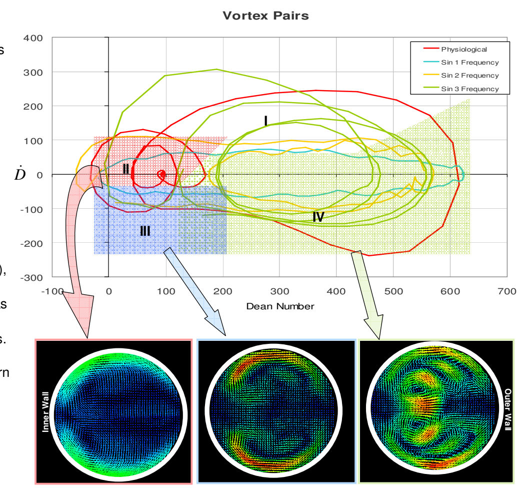

Fig R.2: Plot of four experimental waveforms showing regions classified by secondary flow patterns

CONCLUSIONS

- Complex secondary flows and vortex patterns are found in models of curved arteries subject to physiological forcing at relatively low Womersley numbers.
- Lyne-type vortices were reported to exist only at high Womersley number (>12), however, they were observed in this study at a lower value, even for purely sinusoidal forcing.
- Superposition of harmonics shows that there is a correlation between the secondary flow patterns and two dimensionless parameters, Dean Number and $\dot{D}$.
- Existence of the secondary flow vortices enhances mixing within the artery, therefore decrease concentration of unfavorable biochemicals near the artery wall and could prevent the generation of atherosclerosis.
- These results are useful for predicting the secondary flow structure within the coronary artery for arbitrary flow waveforms, enabling physicians to gain insight into the flow in arteries of individual patients.
- Stent members may interact with theses secondary flows and may even alter them significantly (the subject of continuing work)

ACKNOWLEDGEMENTS & REFERENCES

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[1] "What is Atherosclerosis."*National Heart Lung and Blood Institute.* Web. 21 Apr. 2010. <http://www.nhlbi.nih.gov/health/dci/Diseases/Atherosclerosis/Atherosclerosis_WhatIs.html.>.

[2] Venkatesan, Dr. S., M.D.. "Drug eluting stents bare it all ! and bare metal stents cover it all !." *Expressions in Cardiology.* N.p., 14 Dec. 2008. Web. 20 Apr. 2010. <drsvenkatesan.wordpress.com/2008/12/14/drug-eluting-stents-bare-it-all-and-bare-metal-stents-cover-it-all/ >.

[3] "How Are Stents Placed."*National Heart Lung and Blood Institute.* Web. 21 Apr. 2010. <www.nhlbi.nih.gov/health/dci/Diseases/stents/stents_placed.html >.

[4] D. W. Holdsworth, C. J. D. Norley, R. Frayne, A. Steinman, and B. K. Rutt. Characterization of common carotid artery blood-flow waveforms in normal human subjects. *Physiological Measurements*, 20:219–240, 1999