Applied Rheology | DOI: 10.3933/APPLRHEOL-24-24590 | WWW.APPLIEDRHEOLOGY.ORG

Characteristics of Blood Vessel Wall Deformation with Porous Wall Conditions in an Aortic Arch

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Received: 9.9.2013, Final version: 20.12.2013

Abstract:
Blood vessels have been modeled as non-porous structures that are permeable to solutes mixed in the blood. However, the use of non-physiological boundary conditions in numerical simulations that assume atmospheric pressure at the outlet does not illustrate the actual structural physics involved. The presence of pores in the wall influences wall deformation characteristics, which may increase the risk of rupture in specific conditions. In addition, the formation of secondary flows in a curved blood vessel may add complications to the structural behavior of the vessel walls. These reservations can be addressed by a fluid structure interaction-based numerical simulation of a three-dimensional aortic arch with increased physiological velocity and pressure waveforms. The curvature radius of the arch was 30 mm with a uniform aorta diameter of 25 mm. A one-way coupling method was used between physics of porous media flow and structural mechanics. A comparison of results with a non-porous model revealed that the approximated porous model was more prone to hypertension and rupture. Similarly, the secondary flows found to be an important indicator for the vascular compliance that forced the outer aortic region to experience the largest deformation. Consequently, it is very important to use actual physiological situations of the blood vessels to reach a diagnostic solution.

Key words:
aortic arch, fluid structure interaction (FSI), one-way coupling, wall deformation, physiological conditions, porous media

1 INTRODUCTION

Atherosclerosis is a cardiovascular disease that is primarily related to the effective transport of low-density lipoproteins (LDLs, e.g. cholesterol) across the walls of the main arteries. The localization of atherosclerosis is highly dependent on hemodynamic and biomechanical factors, such as wall shear stress and rheological properties of blood [1, 2]. These parameters are also influenced by complex configurations and the orientation of blood vessels in the human arterial system. For example, wall shear stress may vary if the cross section of the blood vessel experiences a sudden change or if tapered or curved segments appear [3–5]. These situations can be observed in large arteries such as aorta with branches, taper, twist, and curvature [6]. Experimental studies have been conducted to determine the velocity and blood flow patterns in the aorta by using particle image velocimetry techniques [7–9]. To avoid experimental complexities and high cost, numerical simulations have become an effective alternative to such measurements of fluid dynamic parameters. Many researchers have adopted this approach while simulating the parameters for aortic arteries with rigid and impermeable walls [10–12]. However, in actual physical situations, the walls of the vessels are deformable and permeable to the solutes mixed in the blood.

Another important factor in the development of atherosclerosis is the flow-dependent response of the vessel wall structures. Studies have shown that during the circulation of the blood in the aorta, a high blood pressure may induce a pathological state commonly known as aortic dissection. A tear may develop in the intimal layer of the wall and may allow the blood to enter the tear site and influence the other layers as well [13, 14]. Therefore, evaluating the stress distribution in the wall of the aorta is important to predict any relationship between fluid dynamics and structural mechanics. Simulation studies that use the fluid structure interaction (FSI) approach for this evaluation are available [15, 16]. However, in all of these studies, non-physiological boundary conditions were used and the veloc-

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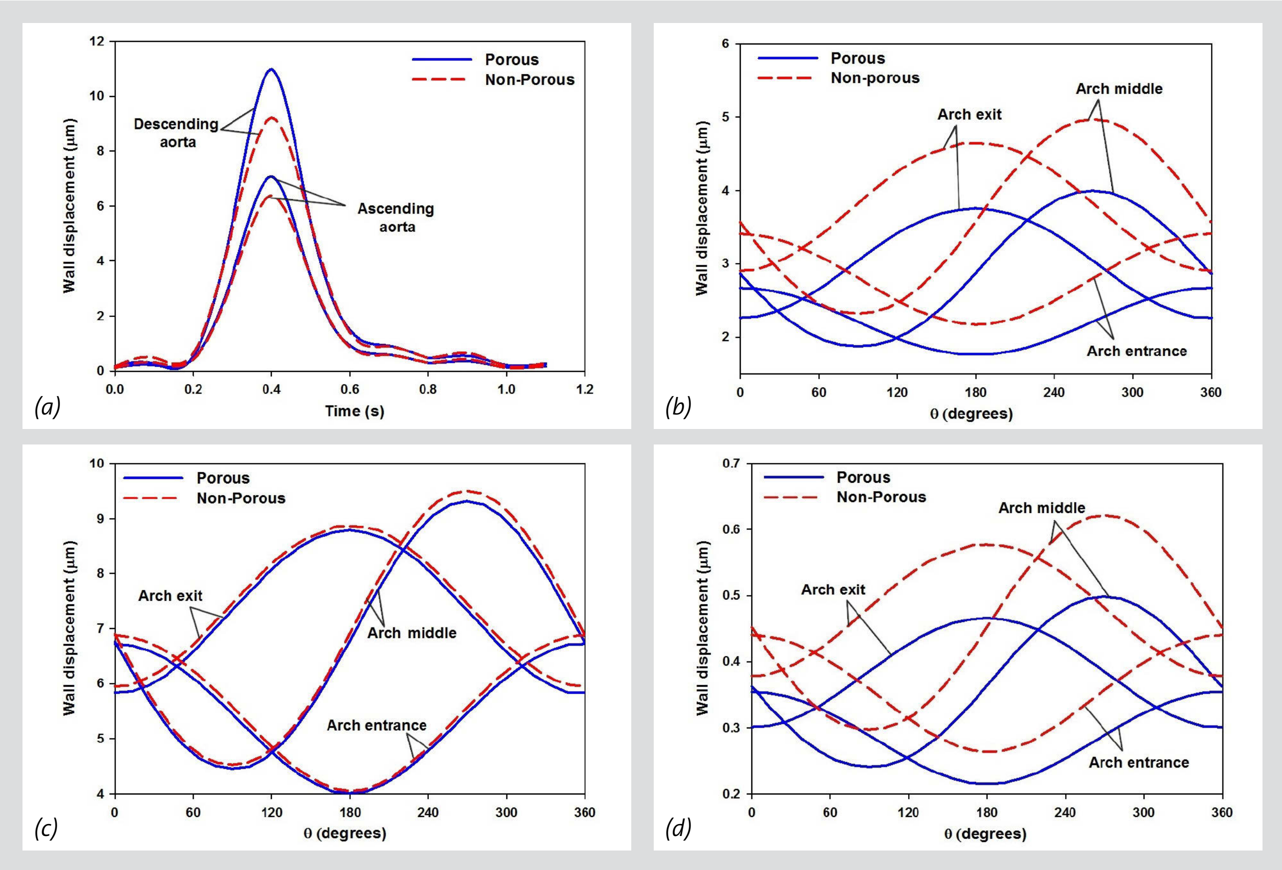

Figure 7: Comparison of porous and non-porous artery wall displacements (in micrometers): (a) Ascending and descending aorta (b) peak systole, (c) peak pressure, and (d) peak diastole in aortic arch.

and outlet boundary conditions at a high Reynolds number. The structural properties of the aortic walls were studied at peak systolic and diastolic velocities and peak pressure by evaluating the average wall shear stress, von-Mises stress, and wall deformation at the fluid solid interface boundary of the model. In addition, these parameters were also studied against Dean number *Dn*, where the importance of secondary flows were considered especially in the curved region of aortic arch.

The results were compared with a non-porous model, and a significant difference was observed, which shows that the porous model, as the approximation of the actual physical model, is more prone to hypertension and rupture. The outer aortic arch region similarly experienced the largest wall displacement and has the least stress. Therefore, this part is the crucial portion in the whole model. In addition, secondary flows could be an important indicator in the deforming walls of the curved aortic arch. The outcome of the study is in accordance with the motivation to study the wall deformation characteristics of porous blood vessels and suggests that the porous structure must be considered for any analysis involving the deformable wall structure. This study would be helpful in predicting the mass transport properties with actual physical situation in the aorta.

ACKNOWLEDGEMENTS

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 2012R1A2A2A01046099), and a grant from the Priority Research Centers Program through the National Research Foundation of Korea (NRF) funded by MEST (No. 2012-0005856).

REFERENCES

[1] Malek AM, Alper SL, Izumo S: Hemodynamic shear stress and its role in atherosclerosis, J. Amer. Med. Assoc. 282 (1999) 2035–2042.
[2] Giannoglou GD, Soulis JV, Farmakis TM, Farmakis DM, Louridas GE: Hemodynamic factors and the important role of local low static pressure in coronary wall thickening, Int. J. Cardio. 86 (2002) 27–40.
[3] Berceli SA, Warty VS, Sheppeck RA, Mandarino WA, Tanksale SK, Borovetz HS: Hemodynamics and low density lipoprotein metabolism. Rates of low density lipoprotein incorporation and degradation along medial and lateral walls of the rabbit aorto-iliac bifurcation, Arteriosclerosis 10 (1990) 686–694.
[4] Karino T, Asakura T, Mabuchi S: Role of hemodynamic factors in atherogenesis, Adv. Exp. Med. Biol. 242 (1988) 51–57.
[5] Sabbah HN, Khaja F, Brymer JF, Hawkins ET, Stein PD: Blood velocity in the right coronary: Relation to the distribution of atherosclerotic lesions, Amer. J. Cardio. 53 (1984) 1008–1012.

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[6] Fung YC: Biomechanics: Circulation, Springer, Berlin (1997).
[7] Kilner PJ, Yang GZ, Mohiaddin RH, Firmin DN, Longmore DB: Helical and retrograde secondary flow patterns in the aortic arch studied by three-directional magnetic resonance velocity mapping, Circulation 88 (1993) 2235–2247.
[8] Seed WA, Wood NB: Velocity patterns in the aorta, Card. Res. 5 (1971) 319–330.
[9] Segadal L, Matre K: Blood velocity distribution in the human ascending aorta, Circulation 76 (1987) 90–100.
[10] Liu X, Pu F, Fan Y, Deng, X, Li D, Li, S: A numerical study on the flow of blood and the transport of LDL in the human aorta: the physiological significance of the helical flow in the aortic arch, Ame. J. Phys. Heart Circ. Physiol. 297 (2009) H163–H170.
[11] Shahcheraghi N, Dwyer HA, Cheer AY, Barakat AI, Rutaganira T: Unsteady and three-dimensional simulation of blood flow in the human aortic arch, J. Biomech. Engg. 124 (2002) 378–387.
[12] Zhang XW, Yao ZH, Zhang Y: Experimental and computational studies on the flow fields in aortic aneurysms associated with deployment of AAA stent-grafts, ACTA Mech. Sinica 23 (2007) 495–501.
[13] Slater EE, Desanctis RW: The clinical recognition of dissecting aortic aneurysm, Amer. J. Med. 60 (1976) 625–633.
[14] Svensson LG, Grawford ES: Aortic dissection and aortic aneurysm surgery: clinical observations, experimental investigations, and statistical analyses. Part II, Curr. Prob. Surgery 29 (1992) 913–1057.
[15] Thubrikar MJ, Agali P, Robicsek F: Wall stress as a possible mechanism for the development of transverse intimal tears in aortic dissections, J. Med. Eng. Tech. 23 (1999) 127–134.
[16] Gao F, Guo Z, Sakamoto M, Matsuzawa T: Fluid-structure interaction within a layered aortic arch model, J. Biol. Phys. 32 (2006) 435–454.
[17] Formaggia L, Gerbeau JF, Nobile F, Quarteroni A: On the coupling of 3D and 1D Navier-Stokes equations for flow problems in compliant vessels, Comp. Meth. App. Mech. Eng. 191 (2001) 561–582.
[18] Taylor CA, Hughes TJR, Zarins CK: Finite element modeling of blood flow in arteries, Comp. Meth. App. Mech. Eng. 158 (1998) 155–196.
[19] Chen ZS, Fan ZM, Zhang XW: The interactions between bloodstream and vascular structure on aortic dissecting aneurysmal model: A numerical study, ACTA Mech. Sinica 29(2013) 462–468.
[20] Benra FK, Dohmen HJ, Pei J, Schuster S, Wan B: A comparison of one-way and two-way coupling methods for numerical analysis of fluid structure interactions, J. App. Math. 2011 (2011) 853560.
[21] Khanafer K, Berguer R: Fluid-structure interaction analysis of turbulent pulsatile flow within a layered aortic wall as related to aortic dissection, J. Biomech. 42 (2009) 2642–2648.
[22] Khanafer K, Bull JL, Berguer R: Fluid-structure interaction of turbulent pulsatile flow within a flexible wall axisymmetric aortic aneurysm model, Eur. J. Mech. B/Fluids 28 (2009) 88–102.
[23] Mills C, Gabe I, Gault J, Mason D, Ross J, Braumwald E, Shillingford J: Pressure-flow relationships and vascular impedance in man, Cardio. Res. 4 (1970) 405–417.
[24] Prosi M, Zunino P, Perktold K, Quarteroni A: Mathematical and numerical models for transfer of low-density lipoproteins through the arterial walls: A new methodology for the model set up with applications to the study of disturbed luminal flow, J. Biomech. 38 (2005) 903–917
[25] Rappitsch G, Perktold K: Pulsatile albumin transport in large arteries: a numerical simulation study", ASME J. Biomech. Eng. 118 (1996) 511–519.
[26] Wada S, Karino T: Theoretical study on flow-dependent concentration polarization of low density lipoproteins at the luminal surface of a straight artery, Biorheol. 36 (1999) 207–223.
[27] Moore JA Ethier CR: Oxygen mass transfer calculations in large arteries, ASME J. Biomech. Eng. 119 (1997) 469–475.
[28] Ethier CR: Computational modeling of mass transfer and links to atherosclerosis, Ann. Biomed. Eng. 30 (2002) 461–471.
[29] Kim WS, Tarbell JM: Prediction of macromolecular transport through the deformable porous media of an artery wall by pore theory, Kor. J. Chem. Eng. 13 (1996) 457–465.
[30] Chung S, Vafai K: Effect of fluid structure interaction on low density lipoprotein transport within a multilayered arterial wall, J. Biomech. 45 (2012) 371–381.
[31] Sheth V, Ritter R: Using computational fluid dynamics model to predict changes in velocity properties in stented carotid artery, Proceedings of the COMSOL Conference, Paris (2010).
[32] Shemer L, Wygnanski I, Kit E: Pulsating flow in a pipe, J. Fluid Mech. 153 (1985) 313–337.
[33] Madhukar V: Mechanics of Materials, Michigan Technological University (2012).
[34] Jarrahi M, Castelain C, Peerhossaini H: Secondary flow patterns and mixing in laminar flow through a curved pipe, Exp. Fluids. 50 (2011) 1539–1558.
[35] Stonebridge PA, Hoskins PR, Allan PL, Belch JF: Spiral laminar flow in vivo, Clin. Sci. 91 (1996) 17–21.

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