CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Various aspects of blood flow through arteries, and their detailed discussion covering experimental, numerical and analytical works are presented in this chapter. Since the present study focuses on carotid artery, its anatomy and morphology is briefed. The analysis of blood flow became interesting and important due to widespread incidence of cardiovascular disorders such as atherosclerosis, aneurysms, coronary infarctions etc. This chapter discusses some of the important observed studies starting from basic numerical simulation, to understand the blood flow using rigid wall approximation on idealistic geometries representing lumen area of blood flow to complex interaction with elastic arteries using different methods of coupled field analysis. This interaction is discussed widely from simple idealistic geometry to image-based patient specific anatomically realistic geometries. Studies carried out in the past are also discussed to validate the numerical simulation results. A very few studies performed clinically and numerically to understand the effects of change in posture on blood flow by considering the gravity effects are also briefed.

2.2 Anatomy and morphology of the carotid artery

The carotid arteries are the main blood vessels that carry essential oxygen-rich blood to the head, brain and face. There are a number of blood vessels that transfer blood through the neck towards the head; and carotid arteries are two of them, which are located on each side of the neck. There are three carotid arteries on either side of the neck: the Common Carotid Artery bifurcates into the Internal and
the External Carotid Artery. Fig-2.1 (a) shows the schematic diagram representing the position of the right carotid bifurcation and Fig-2.1(b) shows the relative positions of all the arteries originating from the aortic arch. The right common carotid artery branches from the brachiocephalic artery and extends up the right side of the neck. The left common carotid artery branches immediately from the aorta and extends up the left side of the neck.

![Fig-2-1](image1.png)

Fig - 2.1: (a) Schematic description of carotid bifurcation, (b) carotid artery origin description (c) carotid artery and vertebral arteries description (d) layers of arterial wall

Each common carotid artery branches into the internal carotid and the external carotid, and there are no branches off the CCA. The ICA is the primary blood supply to the brain and the eyes. The ICA originates at the carotid bifurcation and courses through number of curvatures, through the base of the skull into the Circle of Willis. In contrast to ECA anatomically, there are no branches until it passes through the base of the skull. At the base of the brain, the ICA gives rise to the
anterior and middle cerebral arteries, and the location of this branching is often referred to as the carotid siphon. At the point where the ICA emerges from the common carotid; i.e., immediately after branching, the internal carotid widens a little. This small widening is known as the carotid sinus or carotid bulb. Its shape, length and width can be very different from one subject to the other. The ECA branches off distally from the bifurcation to supply oxygenated blood to the throat, neck, face, scalp etc. The arterial wall consists of three distinct layers or tunics of tissue, as shown in Fig-2.1 (d), which from inside to outside are called: tunica interna or intima, tunica media and tunica externa or adventitia.

**Tunica Intima:** It is the inner most layer, in direct contact with the blood, consisting of a layer of a simple squamous epithelium called endothelium that rests on a connective tissue membrane that is rich in elastic and collagenous fibers. The hollow portion through which the blood flows is known as lumen.

**Tunica Media:** It is the middle layer between intima and adventitia, which is the thickest of the three layers. In the muscular arteries, the tunica media makes up the bulk of the arterial wall. It includes small muscle fibers that encircle the tube and a thick layer of elastic connective tissue. The connective tissue gives to the artery a tough elasticity to withstand the blood pressure force and at the same time stretches in order to accommodate the sudden increase of blood volume that accompanies the opening of the heart valve due to the ventricular contraction of the cardiac muscle.

**Tunica Adventitia:** Tunica adventitia or externa is a thin layer and mainly consists of connective tissue with bundles of irregular thick elastic collagenous fibers. This
layer attaches the artery to the surrounding tissues. It also contains minute vessels (vasa vasorum) that give rise to capillaries and provide blood to the most external cells of the artery wall. The presence of collagen prevents arteries from stretching beyond their elastic limits during peak systole.

2.3 Detailed review of previous studies

The review of referred literature can be broadly classified into experimental, CFD, FSI and influence of posture on blood flow categories.

2.3.1 Experimental research

Numerous experiments have been conducted to study the flow in elastic and rigid tubes or bifurcated branches to examine regions of recirculation and separated flow, which are low shear stress areas or high fluctuating stress zones. The flow disturbance produced by single flow pulses in downstream of stenosis was conducted by (Clark C, 1980), using hot-film anemometry to determine the stenosis influence length and demonstrated the turbulence propagation through the fluid particles flow across the stenosis.

Based on the typical carotid bifucartion geometry, steady flow was investigated in part-I on plexiglass model by (Bharadvaj, 1982) using flow visualization techniques and demonstrated complex flow field in carotid bulb, while the bifurcation apex and side walls were subjected to higher shear stress. In part-II, velocity measurements were performed using laser-Doppler anemometer to obtain quantitative information on the velocity field and to estimate levels and directions of wall shear stress in the region of the bifurcation. A novel method was adopted by (Motomiya, Karino, 1984) to visualize the flow patterns and the distribution of
velocity and wall shear rates by direct observation and photographing the behavior of tracer particles and blood cells flowing through the isolated transparent human carotid bifurcation prepared from post-mortem. Using the unique technique of utilizing vascular casting methods and computer aided analysis, (Levesque et al., 1986) measured the velocity and local wall shear stress using laser Doppler anemometry in casted stenosed aorta. It is observed that larger shape index distribution and elongated cells close to stenosis are associated with high level of wall shear stress.

Velocity measurement across 75% clinically significant stenosis made up of plexiglass was conducted in (Siouffi et al., 1998) using a pulsed Doppler ultrasonic velocimeter, emphasizing on velocity-profile patterns, and discussed that wall shear stress is highly dependent on flow profile. Another experimental validation study was carried by (Gijsen et al., 1999) to investigate the steady flow through carotid bifurcation and unsteady flow through 90° curved tube, using laser-Doppler anemometer demonstrating the influence of non-Newtonian and Newtonian flow. The obtained results were further validated numerically with rigid wall and pulsatile boundary conditions.

A new method based on upstream and downstream pressure measurements across stenosis was developed and validated numerically by (Shalman et al., 2001) to simultaneously measure in-vitro coronary flow reserve and fractional flow reserve. Apart from several flow measurement techniques discussed, the material of test specimen is also important to obtain the satisfactory physiological results. (Tang et al., 2001) developed a thick-wall stenosis model made of Poly vinyl alcohol hydrogel
(PVA) and measured the flow pattern using Duplex ultrasound scanner; the obtained results were validated numerically with close approximation. (Ji et al., 2008) also used the stenosed PVA model to investigate the influence of external pressure on pulsatile flow and deformation across eccentric constriction. The obtained results indicate that Valsalva’s maneuver and cough may cause collapse of stenosis and trigger the plaque rupture.

In another approach, epoxy adhesive was used to create 60% eccentric stenosis in (Ai et al., 2010) to study the flow reversal in post-stenotic region by interfacing micro-electro-mechanical system thermal sensors with the high frequency pulsed wave Doppler ultrasound. The flow profiles in upstream, downstream and at the throat of the stenosis obtained from Doppler ultrasound are in close agreement with the numerical simulation.

Pulsatile flow using PIV to measure unsteady velocity profiles was investigated by (Eguchi et al., 2001.), and demonstrated significant difference between rigid and elastic tube in terms of deviation of flow pattern and shrinking of flexible tube. (Kaminsky, 2007) developed PIV setup to investigate the flow patterns in prosthetic heart valves, treatment procedures using catheters and grafts. The obtained velocity as well as shear stresses is validated with the CFD results.

(Salsac et al., 2004) carried out the experimental study to measure the wall shear stress pattern subjected to physiological pulsatile flow across a cosine shaped model elastic aneurysm. It is also observed that WSS becomes larger as the dilatation ratio increases and the band of re-circulation zones increases with the length of
A novel approach of mock circulatory loop was developed to generate the pulsatile flow using Left Ventricular Assist Device through latex tube as investigated by (Canic et al., 2005). The measured velocity and pressure are in close approximation with that of mathematical models.

An experimental model developed in (Pontiga, Gaytán, 2005) was based on the fundamental laws of haemodynamics, such as Poiseuille’s law, Bernoulli’s equation, or the association of vessels. The basic flow phenomena such as the pressure drop in constricted tube and transition from laminar to turbulent flow are quantitatively investigated. Silicon model of abdominal aortic aneurysm was developed based on CT data in (Frauenfelder et al., 2006). The flow streamlines were visualized and captured through illumination of fluid particles by fanlike split laser beam. The captured flow patterns, before and after stent graft implantation, were validated numerically with close approximation.

2.3.2 CFD analysis

Several investigations are simulated numerically; a few to validate the experimental results and the rest to study the complex and highly disturbed regions with low and high shear stress locations. The review of CFD studies can be broadly classified into Idealised CFD and Subject Specific CFD studies. Most of the initial studies were carried out assuming blood to be Newtonian and with enhanced computational ability; and to investigate the detailed physiological understanding in crucial zones, non-Newtonian studies were then performed.
2.3.2.1 Idealised CFD studies

The flow across simple normal rigid tube ranging from mild to severe stenosis was investigated by (Deshpande et al., 1976) for average Reynolds number. The obtained results are comparable with available experimental data, and its relationship to vascular disease is also discussed. (Perktold et al., 1986) were the first to simulate the blood flow in a 2D idealistic carotid artery bifurcation for average Reynolds number using FEM to solve time dependent Navier–Stokes equations for pulsatile flow.

The blood flow doesn’t exhibit constant viscosity at all flow rates, especially in microcirculatory system and in small branches and capillaries, effectively reducing viscosity through the tube. However, Newtonian behavior is considered in large arteries as viscosity remains constant due to high shear rates as discussed in (Ku, 1997). Experimental investigations carried out separately on 3D carotid bifurcation and 90° curved tube were validated numerically with close approximation under steady state and periodic boundary conditions as presented in (Gijsen et al., 1999), and demonstrated significant differences between Newtonian and non-Newtonian fluid.

A steady axisymmetric flow in a constricted rigid tube was solved numerically in (Pontrelli, 2001) using finite difference scheme and proposed deformation dependent viscosity by shear-thinning fluid. The flow pattern with distributions of pressure and shear stress was investigated and significant difference with Newtonian case was also discussed. Different severities of axisymmetric and asymmetric stenosis were investigated under pulsatile flow conditions by (Long et al., 2001), and clearly demonstrated the formation of highly complex flow separation zones in post-stenotic
region, which increases with increased severity. It was also observed that stenosis influence length exceeds to longer distance in axisymetrical in contrast to asymmetric stenosed conditions. Similarly, (Tambasco, 2002) developed novel computational techniques to track the fluid elements representing blood particles and investigated its influence on flow in normal and mildly/severely stenosed idealistic carotid bifurcation, in addition to straight eccentric stenosis subjected to pulsatile flow.

Important distinct stages of aneurysm formation in curved and bifurcating arteries were investigated numerically in (Foutrakis et al., 1999) and demonstrated the common sites of high pressure and wall shear stress leading to aneurysm formation and growth. The nature of flow recirculation in carotid sinus, bifurcation angle and out-of plane angle of ICA are mainly responsible for initiation of plaque buildup, as discussed in (Nguyen et al., 2008) with applied physiological boundary conditions on idealistic geometric generated based on MRI data. The effects of stenosis severity and wall shear stress were discussed by (Jung et al., 2004) for pulsatile flow and reported that asymmetric flow can be detected in the more than 57% stenosis itself. Intense swirling motion and asymmetric separation in downstream of stenosis is observed due to flow instability at the stenosis.

The plaque shape, location and dimension plays a crucial role in altering the atherosclerotic flow field as discussed in (Lorenzini, Casalena, 2008). Different plaque shapes are numerically simulated and it is reported that factors such as stenotic shape and height affects the flow disturbance; slope of the stenotic walls influences the blood flow recirculation; and increased velocity at throat depends on the shape and height of stenosis.
In another approach, (Sankar, Lee, 2010) demonstrated that mathematical analysis is utilized to solve pulsatile blood flow through mild stenosed arteries by considering the blood in core region as a Casson fluid and the plasma in peripheral layer as Newtonian fluid. It is observed that the results demonstrate better ability of predicting the more interesting haemodynamic features to physiologists because of peripheral layer. Similarly, (Mishra, 2011) have attempted to mathematically model the capillary-tissue exchange phenomenon using mixed coupled boundary and the results obtained correlating well with the experimental observation and demonstrate that deeper region cells are deprived of the nutrients in the stenotic region.

Further, simulation of severe carotid bulb stenosis with ulceration was taken by (Oh et al., 2010); and thus revealing the possibility of CFD analysis and demonstrating the detailed insight into haemodynamics. A novel approach of conducting the feasibility analysis, which demonstrates the potential of simulating the phenomenon of flow induced blood clotting is presented in (Feng et al., 2012) based on discrete particle dynamics (DPD) methodology derived from molecular dynamics approach. The periodic boundary conditions applied on idealistic several stenosed models and flow separation and velocity profiles obtained from CFD results are in excellent agreement with that of DPD observation.

Flow across stenosis/ aneurysm undergoes transition to turbulence, leading to large recirculation zones. The prediction of complex and highly disturbed flow in these zones is mainly influenced by turbulence models adopted in numerical simulation. Reynolds-Average Navier-Stokes (RANS) approach, namely, the k-ω turbulence model is adopted in (Ghalichi, 1998) to study the axisymmetric two-dimensional laminar to turbulent flow in stenosis.
(Molla, 2009) investigated Large Eddy Simulation (LES) using a top-hat spatial grid-filter from the sub-grid scale (SGS) techniques to understand the flow transition-to-turbulent blood flow in arterial stenosis/ aneurysm through simulating the different types of Newtonian and non-Newtonian pulsatile blood flow in a constricted and dilated channel. (Mohammed Abdul Hye, 2012), further extended the LES study with the Smagorinsky-Lilly dynamic subgrid model and two-equation Standard $k - \omega$ transitional turbulence model to investigate non-spiral and spiral blood flow through three dimensional models of arterial stenosis and aneurysm.

2.3.2.2 Subject Specific CFD studies

(Milner et al., 1998) developed patient specific carotid bifurcation models based on MRI data in addition to pulsatile boundary conditions, and proved that idealized geometry provided invaluable measurements, masking the interesting and important in vivo haemodynamic behavior. It is also noted that geometry shape plays a prominent role in determining local wall shear stress patterns, which is the main cause for atherosclerosis. Similarly, phantom and CFD idealistic models based on MRI data were developed by (Marshall et al., 2004). They validated obtained experimental values with the numerical results using pulsatile boundary conditions.

The common sites of high pressure and wall shear stress leading to aneurysm formation and growth was discussed in (Shojima et al., 2004) and (Chien et al., 2008), considering the patient specific models with applied pulsatile velocity inlet boundary conditions. The important role played by wall shear stress can be considered as a prediction of the initiation, growth, and rupture of cerebral aneurysms. The concept of identifying image-based numerical cerebral aneurysm
models at high risk for rupture was discussed in (Cebral et al., 2009). The influence of haemodynamics in assessing the aneurysm just prior to its rupture is discussed, which shall aid in identifying high risk potential of the previously identified haemodynamic characteristics.

(Antiga, 2002) presented a new tool of developing patient-specific carotid bifurcation and abdominal aorta, thus demonstrating the possibility of benefitting clinically by introducing realistic geometries of normal and diseased blood vessels. Considerable difference is noticed between Newtonian and non-Newtonian simulation by applying periodic and time averaged boundary conditions.

Using Spectral Element Method, patient specific carotid bifurcation under pulsatile flow conditions was studied by (Lee et al., 2008), and simulation results demonstrated the weakly turbulent state of the blood flow, with abrupt and complex velocity and pressure fluctuations in the post-stenotic region of ICA and instantaneous rise in wall shear stress at the stenosis unlike normal carotid system. Later, image based patient specific geometric numerical models of carotid bifurcation of normal and mild stenosis is also presented in (Deshpande et al., 2009). The patient specific velocity data are boundary conditions applied based on ultra sound Doppler, and the obtained results highlighted the flow separation, identified with local flow alterations even in mild stenosis, which usually doesn’t affect the overall flow pattern. (Li et al., 2009) studied that apart from peak wall shear stress values, adverse pressure gradient is the main cause for mechanical triggering of plaque rupture. Similar study of image based CFD simulation of idealistic normal and stenosed (eccentric and concentric) carotid bifurcation was carried out by (Yu, 2007) with
average and periodic boundary conditions, highlighting considerable differences between Newtonian and non-Newtonian assumptions. It is also reported that flow behavior was intense and complex with the increased severity in eccentric and has high risk of stroke occurrence when compared with concentric stenosis. In another investigation concerned with thrombus formation, (Rayz et al., 2008) demonstrated the close similarity between numerically simulated intra-aneurysmal regions prognosed with slow, recirculating flows and the regions of thrombus deposition observed in-vivo in the follow-up MR studies. Non-Newtonian assumption demonstrated the close agreement with clinical observation of low velocity zones and clotted-off regions in contrast to Newtonian studies.

(Valencia et al., 2008b) studied several patient specific saccular cerebral aneurysm located at posterior and anterior regions of Circle of Willis under physiological inlet waveforms. The differences between unruptured, ruptured, lateral and terminal aneurysms are discussed and reported that, wall shear stress and pressure showed large variation depending on morphology and size of aneurysm. Similar patient specific cerebral aneurysm was investigated using optimized Lattice Boltzmann solver with a Carreau-Yasuda model as discussed in (Bernsdorf, Wang, 2009), and demonstrated the significant difference between Newtonian and non-Newtonian fluids for different Reynolds number, highlighting the importance of wall shear stress.

Most of the previous studies have utilized the pulsatile flow obtained from ultrasound Doppler scan or by assuming the average Reynolds number as boundary conditions. When patient-specific flow measurements are unavailable, in/out flow
can be estimated by using Murray’s Law as described in (Groen et al., 2010), by defining an empirical relation between outflow and degree of area stenosis. The obtained estimations from Murray’s Law were compared and found to be in close approximation with the flow measurements in the carotid bifurcation using phase-contrast in MRI of patients.

(Wang et al., 2010) presented a unique study of middle cerebral artery aneurysm diagnosed with daughter saccule, and numerically investigated the initiation and growth of daughter saccule by observing the haemodynamic patterns before and after daughter saccule removal. It is further established that aneurysms with daughter saccules have highly complex and unstable flow patterns and hence, prone to rupture.

The aneurysm growth zones have been emphasized in (Acevedo-Bolton et al., 2006) through simulation of different stages of interventional options for treating a giant intracranial aneurysm, based on MRI image data. Another review by (Lasheras, 2007) is based on detailed information stating the influence of mechanical forces responsible for formation sac, growth and finally rupture. In another detailed review, the growth of aneurysm occurs likely in the region of endothelial layer exposed to abnormally low wall shear stress as observed in (Boussel et al., 2008). The important role played by haemodynamic shear stress in treating various cardiovascular diseases such as prediction of restenosis after coronary and peripheral angioplasty, devising a stent strut design, which is less thrombogenic and more conducive to endothelization, identifying the higher risk factor of growth and possible rupture as well as initiation of thrombosis in various cardiovascular diseases
are discussed briefly in (Cecchi et al., 2011). The various application of computational hemodynamic studies pertaining to cerebral aneurysm initiation, progress, and rupture, which provide valuable information for planning and follow-up decisions for treatment are mentioned in (Jeong et al., 2012).

The prevailing controversy of endothelial damage occurring either due to high or low wall shear stress has been stressed by (Meng et al., 2013) and hypothesized that, both high and low wall shear stress are two independent haemodynamically driven by biologic pathways responsible for initiating the intracranial aneurysm growth and rupture. Low wall shear stress and a high oscillatory shear index induces inflammatory-cell-mediated pathway, while mural cell-mediated pathway is induced by high WSS and a positive wall shear stress gradient.

Similar study of 2D patient specific model of stenotic carotid bifurcation considering different k-ε turbulence models is studied by (Stroud, 2002) and suggested that inclusion of a turbulence model was successful in capturing expected details of the flow transition. Pulsatile turbulent flow simulated across moderate axisymmetric stenosis is discussed in (Varghese, 2003) to study the influence of different turbulence models and it is reported that, low Reynolds number k-ω turbulence model is much better than both the low and high k-ε turbulence model and the standard k-ε model.
2.3.3 FSI simulations

It is evident that haemodynamics investigations using rigid wall approximation alone will not be physiologically realistic, as blood flow is highly influenced by elastic behavior of arterial wall. Numerous FSI simulations are investigated to understand the highly complex and altered flow behavior in the surrounding regions of stenosis and aneurysms, and the review of past literature can be broadly classified into idealistic and patient specific studies. Several initial investigations were performed assuming blood to be Newtonian fluid and arterial wall as linearly elastic. In addition, hyper elastic and visco-elastic arterial wall behavior with non-Newtonian assumption are also discussed in recent FSI studies.

2.3.3.1 Idealised arterial model

Idealistic geometry based on previous studies or approximate model obtained from MRI/CT images is mainly classified into Newtonian fluid with linear elastic artery and Newtonian fluid with hyper-elastic behavior of arterial wall. There are also very few studies based on non-Newtonian assumption with linear elastic arterial wall.

Newtonian fluid and linear elastic arterial wall

The importance of 3D geometry on accurate investigation of flow using rigid wall condition is presented in (Perktold et al., 1994) under non-Newtonian pulsatile flow assumptions. It also further demonstrated that compliant analysis with independent structural ring model significantly altered with reduced flow field and wall shear stress in comparison with rigid wall results. Similar flow analysis in (Perktold, Rappitsch, 1995) demonstrated the more realistic wall deformation with the revised non-linear shell assumption. The change in haemodynamics behavior due
to the influence compliant arterial wall during pulse cycle is discussed in detail especially in crucial zones. Based on the MRI scan data, phantom model of normal and stenosed carotid bifurcation is generated and experimental results are validated with the numerical simulation by (Cebral et al., 2001) and affirmed that image-based approximate numerical models are beneficial in investigating the haemodynamics in compliant carotid arteries. The flow changes across idealistic concentric stenosed common carotid under steady and pulsatile flow have been studied in (Lee, Xu, 2002) and mild flow disturbance in post-stenotic zone and its influence on elastic arterial wall is also briefed. Similar study of healthy carotid bifurcation has been carried out in (Tada, Tarbell, 2005) under pulsatile flow conditions and the influence of wall shear stress and structural circumferential stress/strain carotid sinus area, which is highly prone to atherosclerotic plaque formation is discussed.

Most of the applied boundary conditions are either unknown or assumed or obtained from MRI and Doppler devices. In an attempt to apply pulsatile inflow and outflow boundary conditions, 1D model of entire arterial tree is coupled with 3D FSI model in (Urquiza et al., 2006) and obtained results are in good agreement and demonstrate the clinically observed flow pattern. The outcome of synthetic grafts and occurrence of intimal hyperplasia during bypass surgery is studied by (Shaik, 2007). The Newtonian and non-Newtonian studies on preliminary carotid bifurcation also demonstrated the excellent agreement with experimental and clinical observation. It is also discussed that geometry of arteries plays very important and significant role in locating the severe wall shear stress, which are susceptible to the atherosclerosis progression.
Different stenosis levels investigated by (Li et al., 2007) reveals that severe stenoses inhibits arterial wall motion, resulting in higher blood velocities, maximum wall shear stress and localization of circumferential stress/strain, which leads to progression and finally rupture of plaques. The effect of wide range of different linear elastic modulus on blood flow behavior is studied in (Cho et al., 2011) with non-Newtonian assumption; periodic and transient changes in blood flow was noticed. It is discussed that as blood vessel is more elastic, time frame of velocity, pressure and wall shear stress gets longer and flow separation zone gets smaller in addition to severe transient changes in the flow caused due to high arterial wall deformation.

Most of the built-in codes have difficulty in developing coupling algorithms and fail because of classical iterative procedures. To overcome this, semi-implicit coupling methods are proposed by (Quaini, 2009), and verified through simulation of pressure pulse propagation in an idealized carotid bifurcation and the solution remained stable for a wide range of discretization and physical parameters. In strongly coupled field problems, difficulties present in partitioned couplings techniques are studied by (Degroote, 2010) and existing algorithms (IBQN-LS coupling technique) are analyzed, compared and improved; and new algorithms (IQN-ILS technique comparable to monolithic solver) are developed. These simulations demonstrate that the developed algorithms are able to solve complex fluid-structure interaction problems in a partitioned method with black-box solvers.

Another simple study on carotid bifurcation by (Lee et al., 2012) with initial wave propagation validation demonstrated strongly skewed axial velocity and flow
separation in the ICA in carotid bulb with reasonably low wall shear stress. Similar investigation presented on carotid bifurcation in (Toloui et al., 2012), demonstrated considerable difference between non-Newtonian and Newtonian assumptions. It is also discussed that Newtonian model underestimates the value of mechanical stress over the apex, and overestimates the extent of the back flow zone. In both the studies, rigid and flexible wall conditions were simulated; and it is observed that FSI simulation predicted a larger recirculation zone close to carotid bulb, reduced wall shear stress and smaller back flow zone, when compared with rigid-wall model.

Pulse wave propagation simulation is equally important when compared with pulsatile flow boundary conditions. The wave propagation is usually investigated to verify the capability of either in-house developed or commercially available finite element coupled field solvers/algorithms. (Järvinen et al., 2001) developed a loosely coupled FSI solver and tested for simple pressure pulse propagation in an artery. To facilitate the reduced coupling method from 3D to 1D, (Formaggia et al., 2001) proposed a several multi-scale approaches suitable for absorbing the outgoing pressure waves to describe blood flow in arterial system. The influence of pulse wave propagation on wall shear stress studied by (Fukui et al., 2007) suggests that wave propagation reduces the speed of blood, thereby reducing the wall shear stress considerably by 1 Pa, which is significant and plays crucial role in physiological response of arterial wall to blood flow.

(Degroote et al., 2009a) developed a new partitioned quasi-Newton technique and monolithic Newton algorithm capable of solving coupled field problems through partitioned and monolithic ways, respectively and verified through wave propagation
phenomenon in 3D elastic tube with short pressure pulse applied at the inlet. Further, the applications of these developed techniques are useful in coupling the commercially available finite element flow and structural solvers. (Degroote et al., 2009b) also developed the revised algorithm of interface quasi-Newton technique with an approximation for the inverse of the Jacobian from a least-squares model and demonstrated the importance of coupling algorithms known as black box through pulse pressure propagation in a flexible tube

**Newtonian fluid and hyper-elastic arterial wall**

A new method of using commercially available finite element software for analyzing flow behavior in mild and severe concentric stenosis is presented in (Bathe, Kamm, 1999) assuming fluid to be Newtonian and solid arterial wall as nonlinear Odgen model. The obtained results demonstrate significant increase in pressure drop, peak wall shear stress and maximum principal stress, with the increase in severity of stenosis.

Similar observations are discussed in (Tang et al., 1999) for axisymmetric and asymmetric stenosis with thick wall assumptions and extended to thin wall assumptions. The maximum shear stress from the thick-wall asymmetric stenosis model was considerably lower than that from the thin-wall model due to the increased stiffness. Later, (Tang et al., 2003) experimentally investigated the asymmetric stenosed condition and validated with numerical simulation; and demonstrated that severe stenosis is related to artery compression and plaque cap rupture caused due to critical flow conditions, high tensile stress and considerable compressive stress conditions.
The flow dynamics in healthy and aneurysm basilar artery were numerically compared under pulsatile flow conditions in (Valencia, Solis, 2006) and demonstrated the significant complex flow alteration in aneurysm, resulting in wall displacement and effective stress depending on wall thickness and wall model adopted. Also, assuming hyper-viscosity behavior of blood under pulsatile flow conditions, (Valencia, Villanueva, 2006) compared asymmetric and axisymmetric stenosed condition with rigid wall simulation, and discussed that the severity of stenosis depends on flow recirculation length, wall displacement and effective wall stress.

(Canić et al., 2006) mathematically developed 1D finite element model to capture the flow dynamics in idealistic normal artery assuming arterial wall to behave linearly viscoelastic membrane under pulsatile flow and validated with experimental results of (Canić et al., 2005). The proposed simple and efficient model predicts local haemodynamics and wall shear stress of higher order accuracy and be extended to predict the possible pathologies in cardiovascular functions.

Idealistic large and small neck sized aneurysm on straight and curved artery were investigated under steady and pulsatile flow conditions by (Yahya, 2010). It is reported that wall deformation and wall shear stress played an important role in growth and rupture of aneurysms, those which are located especially on highly curved arteries. Another approach was adopted by (Janela et al., 2010) to study the absorbing boundary conditions. Initially developed 1D hyperbolic model to capture the wave propagation was directly coupled with the 3D FSI simulation for different non-Newtonian models and proposed that the developed direct 3D to 1D coupling can also be applied to realistic geometries.
2.3.3.2 Subject specific case studies

The image-based patient specific category is further classified mainly into Newtonian fluid with linear elastic artery and Newtonian fluid with hyper-elastic behavior of arterial wall.

Newtonian fluid and linear elastic arterial wall

(Vinitski et al., 1992) investigated the hemodynamic factors leading to the formation and evolution of atherosclerotic plaque in carotid arteries and aneurysms in the abdominal aorta on both patient and phantom models. The images of patient specific models were obtained by MR and x-ray angiography and the resulting images were digitized using a Vax computer. There was general agreement in the results obtained between MRA, color Doppler, DSA and computer simulation in both phantom and in-vivo experiments.

The regions of high intramural wall stress and development of atherosclerotic lesions in carotid artery bifurcation was studied in (Robert et al., 1995). The carotid bifurcation geometry data is obtained through in-vivo measurements such as MRI slides, ultrasound and angiogram data. Later, with these data two representative 2D finite element models were created in order to determine the areas of localized stress concentration that occurs in the bifurcation.

Carotid bifurcation model is generated based on MRI scan and cadaver specimens by (Salzar et al., 1995), and reported the role played by wall shear stress in atherosclerotic lesion formation, and elevated structural stresses at inner wall surface has potential of causing endothelial cell damage. In another study,
significance of arterial wall motion and blood vessel geometry are highlighted by (Zhao et al., 2000) by comparing the rigid and compliant carotid simulation and discussed the variation of haemodynamics parameters throughout the pulse cycle. Haemodynamics in cerebral artery was investigated to understand the flow dynamics through numerical simulation in (Oshima et al., 2001). 3D geometry of carotid siphon was based on CT data and results obtained demonstrate the distribution wall shear stress and secondary flows behavior along the curvature.

The blood flow simulation in realistic vascular models was studied in (Deschamps et al., 2004), in which the anatomical surfaces were extracted by means of Level-Set methods that can accurately model the complex and varying surfaces of aneurysms and stenosis. The surfaces obtained were defined at the sub-pixel level where they intersect the Cartesian grid of the image domain. Therefore, embedded boundary representations are constructed on the same grid and further discretized to solve Navier-Stokes equations for compressible fluids.

(Juan et al., 2004) highlighted the accurate patient-specific hemodynamic models construction from medical image data and its use for large clinical studies. An iso-surface deformable model is used for stenosed arteries as well as arteries with aneurysms, where the image is first smoothed by convolution with a Gaussian kernel and the voxel intensities are then sharpened. The final model obtained by reconstruction technique (adopting region growing segmentation approach) is then smoothed using a non-shrinking algorithm and vessel branches are interactively truncated and extruded in order to minimize the influence of boundary conditions on the region of interest. Further these models are numerical solved to investigate the haemodynamics at crucial sites.
3D vascular geometry of the diseased arterial segment was reconstructed from a series of 2D cross-sectional images stacked together as discussed in (Lee et al., 2004). The acquired images were segmented to produce smooth lumen and plaque contours by using purpose built software. Later, 3D geometry reconstruction was completed by fitting a 3D surface. Numerical flow simulations incorporating coupled fluid–solid interaction were implemented using flow and pressure waveforms measured in vivo.

Realistic 2D abdominal aorta with mild stenosis was analyzed by (Rinderu et al., 2006) based on the MRI scan data. A stack of rectangular 2D slices from MRI data are precisely positioned and lumen area is segmented for each these slices in which the entire set is fitted with Bezier curves. Finally, 3D model obtained is solved for steady, laminar flow of an incompressible, non-Newtonian fluid and results obtained agreed well with the laser Doppler Anemometry results. (Tabor et al., 2006) have developed tools for generating computational meshes automatically from medical scan data (MRI, CT), allowing the easy creation of patient-specific models of the flow domain. In this applied technique, CAD models are inserted into the original scan data using Scan CAD and thereby enhancing the capability to interactively modify the geometry. Simulations of flow models before and after surgery are compared to study the changes in haemodynamics at crucial sites.

(Alberto Figueroa C, 2006) developed a new monolithic robust coupled-momentum method and emphasized in different outlet boundary conditions such as constant pressure, impedance and resistance boundary conditions influencing the physiological pulsatile flow. Outflow boundary conditions were also discussed by
(Irene, 2006) describing that blood flow in large arteries is highly dependent on the boundary conditions imposed to represent the vascular bed downstream of the modeled domain. It is also described that in cases where flow distribution and pressure boundary conditions are unknown, novel multidomain approach with models of the upstream regions of interest are coupled to reduced-order (0D or 1D) models of downstream vessels. This concept is also adopted in (Järvinen et al., 2008) in addition to new method (artificial compressibility method) to simulate strongly coupled computation of blood flow in an elastic artery, which provided robust convergence.

Further, this concept of coupling to reduced order is also discussed in (Kim et al., 2009) through augmented Lagrangian method. This coupling technique does not include any constraints on the shape of the velocity profiles nor on the distribution of pressure at the interface. A generic 1D distributed model of human arterial tree with primary systemic arteries developed by (Reymond, 2011) was later extended to patient specific 1D model, which predicted the better pressure and flow waveform, closely related to in-vivo measurements. Different types of new preconditioners were implemented and verified by (Crosetto, 2011) exhibiting better and high performance of parallel computing.

(Torii et al., 2006) adopted a new FSI method to compute the fluid mechanics with moving walls using the Deforming-Spatial-Domain(DSD)/Stabilized Space–Time SST) method under pulsatile flow conditions considering the peripheral resistance. A segment of artery was computed for rigid and compliant wall conditions and demonstrated the flow behavior altered under influence of compliant wall.
Similarly, (Torii et al., 2006) investigated MCA bifurcation aneurysm and demonstrated the remarkably large difference of hypertension case over normal blood pressure.

Significance of wall shear stress was highlighted through couple of MCA bifurcation aneurysm simulations as discussed in (Torii et al., 2007) and later significance of artery and different aneurysm shapes were compared and considerable difference between compliant and rigid wall were also highlighted as reported by (Torii et al., 2009). Relatively high flow velocities due to the interaction between the blood flow and aneurysmal wall is found to be independent of the wall model and simulated results in (Torii et al., 2008) showing that both linearly elastic and hyper-elastic models are useful in investigating the risk factors associated with an aneurysm.

Based on 3D rotational angiography data, simulation of several cerebral aneurysms with non-Newtonian assumption is discussed in (Valencia et al., 2008a) and demonstrated that haemodynamics behavior depends mainly on morphology of the artery, aneurysm size and its location. The importance of recovering the zero-pressure state is evaluated by (Vavourakis et al., 2011) as direct utilization of the image-based configuration causes unrealistic wall deformation and underestimation of wall shear stress.

**Newtonian fluid and hyper-elastic arterial wall**

Fully coupled and uncoupled FSI simulations were investigated in (Younis et al., 2004) and discussing the inter-individual variations in flow dynamics and wall mechanics and its effects on atherogenesis, and finally suggested that
Atherosclerosis is multi-factorial and not dependent on a single mechanical factor. Based on DSD/SST, another FSI modeling technique - stabilized space–time fluid–structure interaction (SSTFSI) is discussed in (Tezduyar et al., 2007) and emphasized on model arterial fluid mechanics, considering membrane and continuum element approach separately for arterial wall. The dampening effect on arteries surrounded by tissues is also considered by adding mass-proportional damping. Similar studies were carried out by (Tezduyar et al., 2008, 2009) for different set of aneurysms.

It is very well demonstrated that SSTFSI method is computationally more economical alternative to the fully coupled FSI approach in arterial fluid mechanics, providing additional flexibility. Using the same method, (Takizawa et al., 2011) investigated the lumen geometry generation based on 3D rotational angiography and developed new techniques to improve the estimated zero-pressure arterial geometry conditions. Further assuming non-Newtonian fluid, feasibility of strong coupling outflow boundary conditions with 1D and 0D were discussed in (Toma et al., 2011) on carotid bifurcation. (Lieve Lanoye, 2008) developed an in-house code to strongly couple the fluid and structural solutions using portioned approach, and validated couple of bench mark problems and further extended it to simulate wave propagation in thoracic aorta, abdominal aorta aneurysms, which demonstrated accurate and stable approach applicable to several biomechanical applications.

The rupturing of cerebral artery when wall tension exceeds the strength of the wall tissue is emphasized in (Isaksen et al., 2008), proposing a novel method of predicting rupture risk through simulation. Besides, an attempt to accurately predict the haemodynamics in giant and saccular aneurysm is discussed in (Bai-Nan et al., 2011), based on CT data and patient specific model generated using
MIMICS. Such modeling and analysis technique provides better insight to Neurosurgeons before and after endovascular treatment.

The importance of prestressed condition to avoid significant discrepancies between imaging data and computational model geometry caused due to over-inflation of artery due to large intramural pressure is presented in (Hsu, Bazilevs, 2011), demonstrating the possibility of accurate prediction of vascular flow phenomenon when compared with non-prestressed condition. With different arterial wall thickness combinations, importance of low wall shear stress observed in post-plaque dilated region of carotid bifurcation is investigated in (Lee et al., 2012). Non-Newtonian assumption and significant flow changes affected by geometric factors along with adverse flow conditions leading to possible growth of an atherosclerotic plaque is also discussed.

The atherosclerotic plaque components and arterial wall were modeled separately as discussed in (Tang et al., 2004) and demonstrated that large lipid pools and thin plaque caps are closely associated with critical stress/strain conditions. (Tang et al., 2008) numerically supported the plaque progression hypothesis and discussed that favorable condition for plaque growth depends on structural stress/strain. This observation is supported by (Kock et al., 2008) suggesting that maximal stress levels are located in the upstream and downstream shoulder regions of the fibrous cap, which are useful in assessing plaque vulnerability, and improving risk stratification. (Tang et al., 2009) also showed that plaques with prior ruptures are associated with higher critical plaque wall stress conditions when compared with non-ruptured plaques and that those high critical stress conditions occur especially at ulcer sites.
Accurately assessing the plaque vulnerability is discussed in (Yang et al. 2009), based on modeling approach combined with in-vivo intravascular ultrasound imaging, computational modeling and angiography. In-house software atherosclerotic plaque imaging analysis developed in MATLAB automatically generates the contour plots of lumen, vessel out-boundary, and plaque components enabled with a smoothing filter. The generated contour plots are stacked and combined to obtain the 3D model quite similar to that adopted in MRI segmentation and volume regeneration technique. Later, 3D computed model is further analyzed to assess the plaque vulnerability.

The potential plaque ruptures due to intense wall shear stress and strongly elevated structural stress levels was reported in (Leach et al., 2010) and also noted the substantial impact on altered predicted stress fields due to misrepresentation of plaque features that are smaller than current in vivo imaging resolution limits. The considerable difference in plaque stress levels between symptomatic and asymptomatic patients demonstrated that plaque stress levels as one of the major factors for plaque vulnerability assessment as reported in (Gao, 2010), and it is also discussed that plaque stress levels based on MRI in-vivo images are associated with fibrous cap thickness, lipid core size and fibrous cap surface.

3D multi-component numerical models of human carotid plaques with and without rupture are investigated by (Zhao, 2010) and reported that critical plaque stresses are strongly associated with plaque rupture and can better predict the location of plaque rupture when compared with critical flow shear stresses, plaque stenosis severity and global maximum plaque wall stresses.
(Auricchio et al., 2011) developed a numerical model to assess the relationship between a given carotid stent design and a given patient-specific CA anatomy. Computed angiography tomography (CTA) images are processed in MIMICS to generate the patient-specific CA model and further evaluate the stresses induced in the vessel wall. Later, the performance of self-expanding stent designs is also evaluated in these patient specific models to assess the lumen gain and the vessel straightening.

2.3.4 Influence of posture on blood flow

Initially, clinicians were interested in investigating and understanding the changes observed in blood flow regulation noticed during different postures. The overview of cerebral perfusion and auto regulation, orthostatic hypotension and impaired cerebral reactivity due to different reasons is discussed in (Greene, Lee, 2012). The noninvasive response of cerebral blood flow is studied in (Aaslid 1989) during normocapnia, hypocapnia, and hypercapnia conditions. It was highlighted that auto-regulation occurs within 4.1 s in hypocapnia while the response was bit slow in normocapnia, and hypercapnia conditions. It is observed that relevant information on autoregulatory gain and the cerebral vasomotor state is possible to obtain clinically from noninvasive response studies.

In the normal healthy individuals, the impact of postural change is mainly observed in head and neck region and lower limbs. With the carotid, cerebral and facial arteries as main focus, the posture changes were tried with 100 head-down tilt, standing and supine positions by (Savin et al., 1995). They observed that blood flow velocity was found to vary immediately, but regulated to a steady-state within a few minutes, whereas during the same time, areas of the face were not regulated.
The blood flow velocity in three main arteries: carotid, brachial and femoral arteries were measured in three different postures: supine, 90 degrees head-down-tilt and 90 degrees head-up-tilt by (Azhim et al., 2004). They discussed that flow velocities in brachial and femoral increased by supine to head-down tilt posture and decreased during supine to head-up tilt posture, with minor changes in carotid artery. Apart from measuring flow velocities, their investigation was further extended by (Azhim et al., 2006) to determine heart rate and blood pressure. It was observed that head up tilt resulted in increased heart rate and significant increase in diastolic blood pressure with non-significant change in systolic blood pressure. Similar observations were investigated by (Sheriff et al., 2007) emphasizing more on blood pressure in lower limbs and eye level arterial pressure during head up and head down tilt. Significance of hypotension/orthostatic tension alone induced during postural change was studied in rats by (Raffai, 2006). The suitable adaptation of entire cardiovascular system along with the haemodynamic and regional response during acute and chronic posture change was the major part of their investigation.

The variation in blood flow, heart rate and blood posture due to postural changes in carotid and femoral arteries was evaluated in older patients between men and women by (Castellano et al., 2004). It was observed that large flow changes were observed in the femoral artery than the carotid artery. However, there were no differences between men and women except for minor differences in heart rate response. In order to diagnose the patients suffering from orthostatic hypotension and to study the haemodynamics related to changes in body posture, (Fujikawa et al., 2009) devised a cephalic laser blood flow meter which can be worn on the tragus to investigate the flow changes during change of posture from sleeping to sitting or
squatting posture. This device demonstrated that cephalic hemodynamics can be studied and cerebral ischemic symptoms can be easily diagnosed in subjects during standing posture. In case of carotid occlusion, the cerebral auto regulation is affected and possibility of impaired auto regulation is investigated by (Vernieri et al., 1999). It is suggested that impaired cerebrovascular reactivity is predictive for cerebral ischemic events in patients with carotid occlusion. It was based on obtaining the prognostic indications in patients with internal carotid occlusion on the basis of intracranial hemodynamic status and presence of previous symptoms of cerebrovascular failure. Similar observation on cerebral impairment is discussed in (Reinhard et al., 2003) by estimating the dynamic cerebral auto regulation from spontaneous fluctuations of arterial blood pressure (ABP) and cerebral blood flow velocity (CBFV). It was based on evaluating the correlation coefficient index method in patients with severe obstructive carotid disease and comparing it with transfer function analysis and CO2 vasomotor reactivity.

In another study carried out by (Brown et al., 1986), impaired cerebral reactivity was investigated in patients diagnosed with unilateral or bilateral internal carotid artery occlusion. It was observed that the cerebral reactivity was reduced mildly in side of unilateral occlusion and considerable fall in bilateral occlusion. Using non-invasive method, dynamic cerebral auto regulation was evaluated in patients with carotid stenosis to establish the identification of impaired auto regulation. Such study can help in identifying the patients who are at stroke risk. The impaired cerebral reactivity at the brain tissue level in patients with a symptomatic ICA occlusion was discussed by (Bokkers et al., 2011) using arterial spin labeling in MRI which can help in identifying the brain tissue at risk of future stroke and as such may guide medical treatment.
The influence of carotid stenosis on cerebral auto-regulation was highlighted through clinical study as observed in (Akiyama et al., 1999). A male subject was diagnosed with recurrent syncopal attacks presented with orthostatic hypotension on the head-up tilt test. In addition to this, angiography also showed severe stenosis of the bilateral extracranial carotid arteries. After undergoing, two-staged bilateral carotid endarterectomy, the orthostatic hypotension resolved and the syncopal attacks have disappeared completely. As clinically observed, it was suggested that orthostatic hypotension in the patient was due to dysfunction of carotid baroreceptors resulting from compression of atherosclerotic plaques. It is also speculated that patient’s syncopal attacks were due to stress induced by standing posture which probably stimulated carotid sinus. In similar study carried out on adult Sprague-Dawley rats by (Duan et al., 2011), chronic cerebral hypoperfusion established through stenosis of the bilateral carotid common artery was relieved through surgery resulting in significantly increased cerebral blood flow.

Other than surgery, stenting also was clinically found to be useful in restoring the impaired dynamic cerebral auto regulation in patients with severe/moderate carotid stenosis as observed clinically in (Sung et al., 2004). Orthostatic hypotension and its relation with stroke is investigated by (Eigenbrodt et al., 2000) through evaluation of diastolic and systolic pressure and consensus OH (during change of posture from a supine to standing position) for baseline associations. Thus, measured OH easily helped in identifying the middle-aged persons at risk for stroke. The association between the duration of standing at the work and the progression of carotid intima media thickness was studied by (Krause et al., 2010) using carotid ultrasound Doppler at the beginning of study and end of 4 years. The role of
hemodynamic factors in the progression of atherosclerosis induced by long-term standing has been discussed.

Apart from clinical study, the response of unsteady flow changes in collapsible tubes due to gravity affect was mathematically modeled using one dimensional accurate upwind finite volume Godunov scheme by (Brook et al., 1999). This study is based on physiological applications to demonstrate the possibility of roll waves occurring in collapsible elastic tubes similar to the response of jugular vein of long neck upright giraffe. (Olufsen et al., 2004) developed a basic mathematical model representing the entire systemic circulation based on compartmental approach, which can predict the blood flow and pressure variation required to understand the orthostatic hypotension during change of posture from sitting to standing. Later, (Olufsen et al., 2007) revised the previous prediction model by addition of control mechanisms: autonomic and auto-regulation, and results obtained during postural change from sitting to standing demonstrated the close approximation with physiological data of subjects.

The growing interest in space flights taken up by the astronauts has prompted the keen interest in researchers to analyze the cardiovascular adaptations during the launch and post flight consequences, since the first space flight by Yuri Gagarin. The cardiovascular changes observed during space travel is not the prime objective of the present study, rather the changes observed in the blood flow behavior during different postures is of main concern. The methodology and the boundary conditions adopted in the mathematical models developed to capture the physiological behavior during space flights can be modified and useful in the present study the blood flow behavior for different postures.
The numerical model of detailed arterial circulation with lumped parameter models using a Mac-Cormack predictor–corrector scheme was developed by (Peterson et al., 2002) to understand the changes in orthostatic hypotension. The changes observed in intrathoracic pressure and the effects of hydrostatic pressure were simulated in supine, launch, sitting, and standing postures for 0, 1, and 1.8 G conditions.

The fluid shifts while standing result in pooling of blood in abdomen and lower limbs and reduction in venous return to the heart is discussed by (Janneke Gisolf, 2005) through beat to beat model developed in Simulink (Matlab). The giraffe model is taken as basis to understand the physiological adaptations, and correlate the cerebral perfusion and working of baroreceptors in humans. Further, their major objective was to predict orthostatic tolerance of astronauts after spaceflight after demonstrating the influence of auto-cerebral regulation. Similarly, (Verheyden 2007) with the clinical experiments demonstrated the cardiovascular adaptation in maintaining orthostatic tolerance and baroreflex function during spaceflights.

The solution to consistent problems faced by astronauts in overcoming the pre and post-flight adaptations is provided by (Bhaskaran, 2008, 2009). It is discussed that regular practice of sheershasana, a yogic posture tunes the cardiovascular system to the pooling of the blood in the head. It was demonstrated through clinically measured ECG, heart rate and blood pressure from different sets of volunteers with the help of 360° tilt table for different postures.
Apart from conventional clinical and analytical methods to demonstrate the influence of gravity on blood flow, numerical investigations were investigated on six types of gravity benchmark problems to understand the gravitational effects on circulatory system (Sung et al., 2004). This study was extended to patient specific carotid bifurcation and Circle of Willis under altered gravity conditions (Kim et al., 2006). Significant effects on arterial wall deformation and consequent changes in flow conditions were demonstrated through transient numerical FSI solution during different postures such as supine, hand standing and standing under auto-regulation.

Numerically developed cerebral vasculature by (Alirezaye-davatgar, 2006) simulates the conditions of G force in blockage of ICA and its effect on cerebral circulation. The modified vasculature of the whole body is developed to obtain the realistic simulation of blood flow under different conditions, and the governing equations were solved by Lax-Wendroff and MacCormack methods. Considerable physiological changes in blood flow in the systemic and cerebral vasculature was observed through the realistic simulation results under the influence of gravitational conditions.

The 2D CFD analysis of idealistic single blood vessel under different postures ranging over several angles from head-up tilt to head down tilt was investigated by (Mu, 2012) to predict the suitable body posture for astronauts. This initial and basic study provides theoretical evidence for cardiovascular modeling in microgravity and would be beneficial to the researchers in designing defense devices for astronauts or patients clinically.
2.3.5 Summary

Till date, most of the research investigations have studied with rigid (CFD) and flexible wall (FSI) assumptions with Newtonian and non-Newtonian flow characteristics. The flexible arterial wall is assumed to exhibit both linear and non-linear (hyper elastic) behavior applied with Odgen and Mooney-Rivlin models. FSI interface is modeled with monolithic and partitioned loosely/strongly coupled two-way interactions. Several experimental studies are carried out on elastic and rigid specimens under steady and pulsatile flow conditions to measure flow patterns and critical shear stress regions. The aforementioned assumptions are considered in the recent studies based on idealistic and image-based patient specific geometries applied to normal and diseased conditions such as stenosis, aneurysm models and interaction with stents and grafts. However, numerical simulations based on altered gravity and its effects on haemodynamics are hardly studied.

The available literature related to different postures and their influence on blood flow is clinically supported, especially for space flights and a few of them emphasize on change of posture from sleeping to standing and from sleeping to head down position. There are sufficient clinical studies which demonstrate the influence of carotid stenosis on impaired cerebral auto regulation. But there are very few clinical studies, which supports the influence of posture and carotid stenosis on orthostatic hypotension and stroke risk associated with the posture change. Also, there are limited studies to support the recovery of impaired cerebral reactivity and orthostatic hypotension upon surgical treatment of carotid stenosis. Unfortunately, there are no such clinical studies available which establish the influence of carotid stenosis and impaired auto regulation related to head down posture. However,
numerical studies related to image-based patient specific coupled-field investigations subjected to altered gravity are also yet to be studied. Hence, to support the clinical observation of blood flow changes in different postures, numerical investigations is carried out in the present study and haemodynamics changes observed discussed to bring out the possible outcomes in diseased cases such as stenosis/aneurysms in contrast to normal behavior.