CHAPTER 7

EFFECT OF POSTURAL CHANGES ON
SUBJECT SPECIFIC CASES

7.1 Overview

Although advances in radiological imaging modalities has facilitated the
diagnosis of several complicated cardiovascular diseases such as atherosclerosis and
aneurysms, but they fail to provide the underlying mechanisms about
haemodynamics in such abnormalities, considering actual physiological functions.
Moreover, there are no such experimental and clinical methods, which can provide
the detailed flow dynamics and help in evaluating the effect of flow complications in
physiological conditions. On the other hand, the usefulness of both CFD and FSI
numerical simulations are well established, and are of great help in determining the
actual flow behavior.

Several past studies have employed the approximate, idealistic models and very
few have analyzed the realistic subject specific cases to demonstrate the
haemodynamics variation in cardiovascular disorders. Thus, the present study deals
with the investigations carried out on anatomically realistic, physiological, subject

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1 Numerical analysis of blood flow in normal and stenosed patient specific carotid bifurcation under
different postures: Part-I, *Australian Physical and Engineering Sciences in Medicine* (Communicated)

8 Numerical analysis of blood flow in severely stenosed patient specific carotid bifurcation under
different postures: Part-II, *Australian Physical and Engineering Sciences in Medicine* (Communicated)

* Part of this chapter is Patient specific Fluid-Structure Interaction study of cerebral aneurysm, 2013,
specific cases, focusing on understanding the haemodynamics in some of the most common ailments of patients such as stenosis and aneurysm. The significant changes observed in flow behavior during postural change in subject specific cases are presented in this chapter. The four different examples of subject specific carotid bifurcation cases ranging from normal to mild and severe stenosis are discussed. These examples demonstrate the application of FSI to provide solution to understand the significance of changes in the flow behavior during different postures such as sleeping, standing and head-down position. Each example is described separately, covering the case details, FSI model generation and discussion on comparison of results obtained.

7.2 Case-1: Normal carotid bifurcation

7.2.1 Case description:

In the present case, healthy normal carotid bifurcations on both sides are considered to evaluate the importance of flow behavior in different postures. The patient had a stroke; however, on evaluation both extra-cranial carotid systems were normal. The geometric model is generated based on data obtained from CT angio scan. Fig-7.1 shows the different views of CT scan data and the encircled area highlights the location of carotid bifurcation on both left and right side in addition to the 3D geometric model generated in MIMICS. The CT angio scan is obtained from a 35 year old female subject. Although the geometry of both left and right side carotid bifurcation is slightly different, but there are no sites of plaque formation as observed in the CT angio scans.
Fig-7.1: Different views of CT scan of case-1 carotid bifurcation, [A] Right and [B] left side
7.2.2 3D FSI models

The 3D CAD models are generated in CATIA based on the export data obtained from MIMICS. The FSI models of each case (both left and right carotid bifurcation) are generated in ANSYS WORKBENCH. The detailed methodology of mesh generation is already discussed in Chapter-3.

The FSI model consists of hexahedral meshed fluid (blood) and solid (arterial wall) models. This common process is adopted for the rest of the other subject specific cases as discussed in this chapter. The grid size of left side carotid bifurcation consists of 34550 and 24520 hexahedral elements for fluid and solid model respectively, while the right side carotid bifurcation consists of 35600 and 27120 hexahedral elements for fluid and solid model respectively, as shown in the Fig-7.2. The density and viscosity of fluid models is assumed to be 1060 kg/m$^3$ and 0.004 Pas, while the elastic modulus of arterial wall is considered as 5 MPa, Poisson ratio of 0.49 and density, 1200 kg/m$^3$ ((Tezduyar et al., 2007), (Kim et al., 2009)) and same material property of both fluid and solid is adopted in rest of the subject specific cases discussed in this chapter.

Since both the left and right carotid systems appears to be normal without any traces of atherosclerosis, time varying velocity and pressure waveform is applied at inlet and outlet respectively similar to that adopted in the idealised carotid normal and stenosed models in the chapter-5. The sequentially coupled transient FSI analysis is carried out for three pulse cycles; and the computed results at third cycle during early systole, peak systole and late diastole are considered for analysis purpose.
7.2.3 Results and Discussion

The changes in flow behavior during various postures are investigated by considering the important haemodynamic parameters such as WSS, velocity contours, wall deformation and pressure profiles. The maximum changes in the flow occur during peak systole, so this instant of pulse cycle is considered to describe the comparison of various subject specific cases for three different postures.

Fig-7.2: Case-1 Carotid bifurcation FSI models (Both left and right side is normal)

However, the changes in flow behavior are almost similar without significant changes in supine and standing position than compared to head-down position. Hence, the plots of pressure, WSS, arterial wall stress, arterial wall deformation contours and velocity streamlines are shown arbitrarily during one of the postures for left and right FSI models rather than describing for all the three postures for all the cases. The flow variation during postural change is presented in the table-7.1 for case-1. The values are measured at the maximum variation in haemodynamics within the fluid/structural models that is at peak systole. There is a decrease in flow
variables during change of posture from sleeping to standing (represented by downward arrow), while there is an increase from sleeping to head-down position (represented by upward arrow) and similar method is adopted in case-2 (Table-7.2), case-3 (Table-7.2) and case-4 (Table-7.2).

Even though in this case both left and right carotid bifurcations are normal and healthy, the minor differences observed among the flow variables are because of the different geometries. The WSS, pressure and wall deformation values are found to be on higher in right carotid bifurcation in contrast to the left carotid bifurcation. However, the flow velocity has minor differences because of the similar flow manner in CCA and flow split up in ICA and ECA. The percentage variation in flow variables during change of posture from sleeping to standing and sleeping to head-down is presented separately as shown in the Fig-7.3 and 7.4. It is seen that the flow behavior changes abruptly with higher percentage during change of posture from sleeping to head-down than compared with sleeping to standing. The changes observed in each haemodynamics parameter and its clinical significance is described individually to understand the flow physiology in normal and healthy carotid bifurcation.

Table-7.1: Variation in haemodynamics parameters observed in left and right side normal carotid bifurcation during change of postures

<table>
<thead>
<tr>
<th>Flow variables</th>
<th>Sleeping to Standing</th>
<th>Sleeping to Head-down</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>Velocity change (m/s)</td>
<td>0.145</td>
<td>0.139</td>
</tr>
<tr>
<td>WSS change (Pa)</td>
<td>0.619</td>
<td>0.834</td>
</tr>
<tr>
<td>Pressure change (Pa)</td>
<td>85.672</td>
<td>101.972</td>
</tr>
<tr>
<td>Wall deformation change(mm)</td>
<td>0.03</td>
<td>0.019</td>
</tr>
<tr>
<td>von Mises stress (Pa)</td>
<td>572</td>
<td>1210</td>
</tr>
</tbody>
</table>
Fig-7.3: Percentage variation during change of posture from sleeping to standing - Case: 1

Fig-7.4: Percentage variation during change of posture from sleeping to head-down - Case: 1
7.2.3.1 Velocity

The velocity contours of left and right carotid bifurcation are shown in the Fig-7.5 during head-down and sleeping positions respectively. The right common carotid is curved, while the left common carotid is straight, before bifurcating into ICA and ECA. Due to the higher curvature of ICA than ECA in bifurcation models, the flow separation occurs mainly in outer wall of ICA with increased flow towards inner wall of ICA as clinically observed ((Milner et al., 1998), (Bharadvaj et al., 1982)). The flow is characterized by steep velocity gradient at the bifurcation region and stagnant/ reversed flow along the outer wall of ICA ((Ku, 1997), (Perktold, Rappitsch, 1995)). Because of the different geometries of ICA and ECA branching in left and right carotid bifurcation models, the flow velocity is higher in ICA than in ECA of right carotid bifurcation. On the contrary, the flow in left carotid bifurcation is equally distributed with slightly higher magnitude in ICA than in ECA.

As observed in (Deshpande et al., 2009), during peak systole, the velocities in ECA and ICA of both right and left carotid bifurcation are comparable. However, during the rest of the pulse cycle, the flow is generally higher in ICA than in ICA. During later part of pulse cycle, as the flow decelerates the flow recirculation especially in outer ICA and bifurcation zone is quiet intense with large flow separation unlike during the peak systole, similar to that observed in (Tezduyar et al., 2007)(Ku, Giddens, 1983). Chapter-5 dealt with straight, idealistic geometry of common carotid, whereas in this chapter, the haemodynamics of subject specific realistic anatomical models demonstrate actual flow phenomenon. With the change of posture, the velocity changes abruptly in both the carotid bifurcation models as shown in the Fig-7.6 with similar pattern.
Fig - 7.5: Comparison of velocity streamlines during peak systole in case-1

Fig-7.6: Maximum velocity comparison for various postures in case-1
During head-down position, the velocity increases tremendously by two to three times in comparison to the sleeping position (refer table-7.1 and Fig-7.4). The flow separation and vortex formation in bifurcation region is highly disturbed in head-down position when compared with sleeping and standing posture. The velocity in standing position decreases 25 to 30% with mild variation in flow separation according to the table-7.1 and Fig-7.3.

7.2.3.2 Wall Shear Stress

WSS is one of the most interesting haemodynamic parameters, because it is directly related to the degeneration of vessel wall. A comparable pattern of WSS distribution with minor changes is observed from the Fig-7.7 at peak systole in left carotid bifurcation and right carotid bifurcation during standing and sleeping postures respectively. The WSS is found to be maximum along the inner wall of carotid bulb near the bifurcation apex, much higher than in CCA and very low towards the outer wall of ICA where flow separation is found be intense ((Groen et al., 2010), (Antiga, 2002)). In ECA also, WSS is observed to be intense towards distal side of inner wall and low close to the root at bifurcation location.

The low flow zone is found to be more intense in right carotid unlike left carotid. Hence, the low wall shear stress in the outer wall of ICA and at the bifurcation zone is quite less (> 0.4Pa) resulting in endothelial dysfunction and more prone to stimulate atherosclerosis (Malek, Alper, 1999), (Meng et al., 2014). However, the maximum wall shear stress along the inner wall of ICA and ECA in both the carotid bifurcations is within the normal range (1-7Pa) even during head down position which actually protects from atherosclerosis(Younis et al., 2004).
Fig-7.7: Comparison of wall shear stress contours during peak systole in case-1

Case-1: Left – Standing

Case-1: Right – Sleeping

Fig - 7.8: Wall shear stress comparison for various postures in case-1
Magnitude of WSS at different zones in normal carotid bifurcation and their marginal level is found to be similar to that as discussed in (Ku et al., 1985). The right carotid bifurcation has higher value of WSS in contrast to the left carotid bifurcation, especially at the inner wall due to highly skewed geometry of ICA (Crosetto, 2011). Because of the carotid bifurcation curvature, there is an increase or decrease in the velocity gradient at entrance or exit of the curvature respectively, and thus these gradients will increase or decrease the WSS. The changes found during different postures are compared in the Fig-7.8 through the entire pulse cycle.

The change of posture from sleeping to standing drops the WSS by 40-45%, as observed from the percentage variation (Fig-7.3); while change to head-down position results in remarkable increase by more than six times. It is also noticed from table-7.1 that the WSS in left exceeds the right carotid system. The WSS is found to be less disturbed without any major complexity due to normal flow behavior as both the carotids are diagnosed normal without any traces of plaque sites.

7.2.3.3 Pressure

The pressure contours at peak systole is shown in the Fig-7.9 in left and right carotid bifurcation during sleeping and standing postures respectively. Both the carotids appear to be normal without any traces of plaque formation, demonstrating the typical pressure distribution (Zhao et al., 2000). The pressure at the bifurcation tip increases as the flow distributes into ICA and ECA at the bifurcation tip, leading to velocity drop. The different curvature as observed at the bifurcation zone, ICA and ECA has slightly altered the pressure distribution in both the carotids (Nguyen et al., 2008).
Fig-7.9: Comparison of pressure contours during peak systole in case-1

Fig-7.10: Pressure comparison during various postures in case-1
The distribution pattern is comparable in ECA and ICA at peak systole of left carotid, while in right carotid bifurcation, ECA exceeds the ICA due to the large flow separation at the carotid bulb ((Oh et al., 2010),(Yu, 2007)). The right CCA is slightly curved increasing the pressure distribution unlike the left CCA, which is almost straight as observed. Fig-7.10 compares the pressure variation in the entire pulse cycle during various postures. The pressure behavior rises instantly during peak systole and gradually reduces as flow decelerates towards diastole. Therefore, the right carotid exceeds the left carotid, highlighting significant difference during peak systole as compared with the rest of the pulse cycle. The pressure drops by less than 5% during change of posture from sleeping to standing due to normal and healthy nature of carotid as observed from the percentage variation comparison in the Fig-7.3. Also, the posture change from sleeping to head-down observes a steady rise of 20% according to the Fig-7.4. Among the various postures, the intense increase in pressure is noticed at the bifurcation tip during the head-down position than compared with the standing and supine case.

7.2.3.4 Wall deformation

Fig-7.11 shows the arterial wall deformation obtained at peak systole during sleeping and standing posture. In the present normal and healthy carotid bifurcation case, the maximum location in both the carotids occurs at the bifurcation region, preferably at the entrance area of ICA and ECA due to the reduced structural stiffness as a result of bifurcation curvature. Ideally, the wall deformation is associated with maximum pressure location, especially at the bifurcation apex. The bifurcation curvature reduces the wall stiffness, and thus has lower value of wall deformation in contrast to the straight idealized geometry ((Zhao et al., 2000),(Tada, Tarbell, 2005)).
Fig. 7.11: Comparison of wall deformation contours during peak systole in case-1

Fig. 7.12: Wall deformation comparison for various postures in case-1
Apart from the maximum wall deformation location i.e., bifurcation region, comparatively the outer wall region of ICA is also subjected to moderate levels of deformation. This combination of low WSS, sufficient higher wall deformation and flow separation can aggravate the atherosclerotic disorders (Taylor, Humphrey, 2009). The obtained deformation values during sleeping position are within 10% of lumen diameter (Perktold, Rappitsch, 1995).

Fig-7.12 describes the wall deformation behavior throughout the pulse cycle during different postures in both the normal carotid bifurcations. There is no remarkable difference among sleeping and standing postures in both the carotids. However, the right carotid marginally exceeds the left carotid during head-down position. The percentage change in variation during change of position from sleeping to standing notices a drop of less than 5% as observed from the Fig-7.3 (Kim et al., 2006). The change of posture from sleeping to head-down position notices a rise in 25% (Fig-7.4). The obtained deformation pattern shows considerable change during different postures and agrees well with the clinical observation (Savin et al., 1995).

7.2.3.5 Structural Stress
As discussed in chapter-5, von Mises stress is used to evaluate the structural stresses developed in arterial wall during pulsatile flow. Fig-7.13 shows the von Mises stress at peak systole during head down and sleeping position in left and right carotid bifurcation respectively. The maximum value of structural stress is located at the inner surface of arterial wall at maximum pressure loads as observed at bifurcation apex in both the carotids(Younis et al., 2004)(Arroyo, Lee, 1999).
Fig - 7.13: Comparison of von Mises stress contours during peak systole in case-1

Fig-7.14: von Mises stress comparison for various postures in case-1
Slightly lower stress distribution compared to the apex is also observed in the entire bifurcation region in both the carotids. Moreover, as there is no site of atherosclerotic lesion formation, typical normal stress distribution is observed in both the left and right carotids. The stress plots shown are slightly transparent to describe the stress distribution at the inner wall. The maximum structural stress is found to be in right carotid system than the left carotid bifurcation due its tortuous geometry causing maximum pressure loads. The stress concentration factor defined as the ratio of the local stress to the uniform stress in the common carotid is 3.1 and 4.3 in the apex region of left and right carotid respectively during sleeping posture (Perktold, et al., 1994). The steep stress gradients are also observed along the outer wall of ICA at the bifurcation zone and distal side ECA in both the carotids during different postures. The lower stress regions observed in these locations are found to have considerable arterial wall deformation.

Another interesting to note is the overlapping of low regions of wall shear stress and location of maximum von Mises stress at the bifurcation region influences the atherosclerotic lesion progression (Perktold, Rappitsch, 1995). However, in head down position, the maximum wall shear stress has slightly crossed the normal range of wall shear stress (7 Pa) and overlap with the structural stress shall promote the atherosclerotic progression (Zhao et al., 2000)(Bathe, Kamm, 1999). The variation of von Mises stress in all the three positions is compared in the Fig-7.14. The minor variation is observed between sleeping and standing posture in both the carotids with significant variation between sleeping and head down position. The maximum structural stress variation is found to be 20% more in right carotid than in the left carotid system. The stress distribution during peak systole drops by less than 2%
during change of posture from sleeping to standing (Fig-7.3), while there is an increase of more than 10% during the change of posture from sleeping to head down position (Fig-7.4). Hence there is considerable difference during change of posture from sleeping to head down position unlike change from sleeping to standing position in both left and right carotid system.

7.3 Case-2: Partial stenosed and normal carotid bifurcation

7.3.1 Case Description

This case refers to a 75 year old male patient who is diagnosed with a right cerebral infarction (stroke). The left carotid system was normal, right CCA was normal with partial narrowing (stenosis) of the entire visualized cervical segment of ICA. The percentage of area reduction is chosen at different locations in ICA and the average narrowing is approximately 60%. The partially stenosed right ICA is highlighted in three different views as shown in the Fig-7.15[A], and similarly the normal left carotid bifurcation is shown in the Fig-7.15[B].

7.3.2 3D FSI Models

The 3D FSI model consists of separately meshed fluid (blood) and solid (arterial wall) models. The grid size of left side carotid bifurcation consists of 32350 and 22350 hexahedral elements for fluid and solid models respectively, while the right side carotid bifurcation consists of 33420 and 26820 hexahedral elements for fluid and solid models, respectively as shown in the Fig-7.16. As the left carotid system appears to be normal, while right ICA has partial narrowing, it is assumed to apply time varying velocity and pressure waveform at inlet and outlet respectively similar to that adopted in case-1.
Fig-7.15: Different views of CT scan of case-2 carotid bifurcation,
[A] Right – partial ICA stenosis and [B] Left side – normal
7.3.3 Results and Discussion

The change in flow parameters during change of posture from sleeping to head-down and sleeping to standing is compared in the table-7.2 at peak systole. The partial narrowing of complete ICA on right carotid bifurcation has increased the flow behavior moderately when compared with the left carotid bifurcation.

Table-7.2: Variation in haemodynamics parameters observed in partial narrowing of complete ICA in right carotid bifurcation and normal left side carotid bifurcation during change of postures

<table>
<thead>
<tr>
<th>Flow variables</th>
<th>Sleeping to Standing</th>
<th></th>
<th>Sleeping to Head-down</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>Velocity change (m/s)</td>
<td>0.224</td>
<td>0.26</td>
<td>1.16</td>
</tr>
<tr>
<td>WSS change (Pa)</td>
<td>1.987</td>
<td>2.386</td>
<td>17.212</td>
</tr>
<tr>
<td>Pressure change (Pa)</td>
<td>210.05</td>
<td>243.45</td>
<td>2053.20</td>
</tr>
<tr>
<td>Wall deformation change(mm)</td>
<td>0.015</td>
<td>0.029</td>
<td>0.188</td>
</tr>
<tr>
<td>Von mises stress (Pa)</td>
<td>2136</td>
<td>4062</td>
<td>21866</td>
</tr>
</tbody>
</table>
Fig-7.17: Percentage variation during change of posture from sleeping to standing - Case: 2

Fig-7.18: Percentage variation during change of posture from sleeping to head-down - Case: 2
Since the percentage of narrowing is 60% and clinically it is treated as having low risk factor. However, the patient should be regularly examined for disease progression and diagnosed for stroke symptoms. The percentage change in haemodynamics parameters during change of posture from sleeping to standing and from sleeping to head-down is plotted separately as shown in the Fig-7.17 and 7.18 at peak systole. The minor change in velocity and pressure among both the carotid bifurcations is observed, while sufficiently large variation is noticed in wall deformation and WSS during change of posture from sleeping to standing. However, sleeping to head-down change in posture has large WSS variation when compared to rest of the flow parameters.

7.3.3.1 Velocity

The velocity streamline contours at peak systole is shown in the Fig-7.19 during head-down and sleeping position in left and right carotid bifurcations, respectively. The partial narrowing of concentric nature in right ICA has substantially increased the flow velocity at the higher location of stenosed region. It is widely known that if the area reduction is less than 70%, the flow sharing does not change significantly. However, in the present case, the flow pattern in stenosed carotid bifurcation is moderately altered in comparison with the left side normal and healthy carotid bifurcation; whereas, similar flow pattern is demonstrated in CCA of both the carotids. Flow separation can be clearly observed at the bifurcation region, especially at the carotid bulb oriented towards ICA root of both the carotids ((Ku, 1997), (Lee et al., 2012)). The flow separation zone extends to longer range towards distal part of right ICA due to partial stenosis as compared with normal left ICA.
Fig 7.19: Comparison of velocity streamlines during peak systole in case-2

Case-2: Left – Head down

Case-2: Right – Sleeping

Fig 7.20: Maximum velocity comparison for various postures in case-2
The normal left carotid bifurcation demonstrates the typical flow distribution at the bifurcation tip with higher flow rate in ICA than in ECA, however left ICA restricts flow moderately and partially diverts the remaining flow towards left ECA (Deshpande, et al. 2009). The right carotid bifurcation has increased velocity ranges in comparison with the left carotid, and similar behavior is found for all the postural changes as observed from the Fig-7.20 during the entire pulse cycle. At the peak systole, the difference between both the carotids is mentioned in the table-7.2. The percentage variation in change of posture from sleeping to standing highlights the decrease in velocity in the range of 35% as shown in the Fig-7.17, while significant raise by more than three times is observed in the Fig-7.18.

7.3.3.2 Wall Shear Stress

WSS comparison of left and right carotid system is shown in the Fig-7.21 at peak during sleeping and standing postures respectively. In the left side, carotid system is diagnosed to be normal; but, WSS profile is quite distinct unlike typical WSS pattern in carotid bifurcation, because of the extremely tortuous ECA and ICA. The WSS is moderately higher in CCA, drops drastically at the bifurcation region, and increases again at inner wall of ECA and ICA at distal end. Due to mild stenosis of complete ICA till distal end, the WSS behavior is highly disturbed, particularly in the bifurcation region (Younis et al., 2004). At this location, flow separation is found to be quite intense, resulting in significantly low WSS, covering larger area in CCA and ICA. Also, there is significant rise in WSS, near the apex towards the inner wall of ECA, and maximum at stenosed region in right ICA ((Groen et al., 2010), (Lee et al., 2012)). The highly disturbed flow in the right carotid bifurcation will increase the vortex formation and further induce the atherosclerotic damage to arterial wall.
Fig - 7.21: Comparison of wall shear stress contours during peak systole in case-2

Fig-7.22: Wall shear stress comparison for various postures in case-2
Such a kind of severity is not observed as the flow disturbance is minimal at the bifurcation zone in the normal left carotid system despite complex curvature of ECA and ICA ((Ku, 1997), (Kock et al., 2008)). The right carotid has higher deviation in WSS than the left carotid as observed during comparison of various postures, as shown in the Fig-7.22. The wall shear is quite low in right carotid (>0.3Pa) when compared with the left carotid (>0.5Pa) due to partial occlusion. The shear stress is distributed to larger area occupied by ICA and at bifurcation zone, thus stimulating the aggravation of atherosclerosis and inducing endothelial dysfunction ((Davies et al., 1986)(Malek, Alper, 1999)). Also, the higher wall shear stress at the maximum stenosed region, especially during head down position will increase the platelet aggregation and accelerating the plaque formation and increasing the risk of thrombosis ((Kozlov et al., 2012)(Cecchi et al., 2011)).

The right carotid peak systole wave has shifted slightly towards mid diastole, while the left carotid pulse wave form is comparable to that of typical carotid pulse wave. The shift is again due to the mild narrowing of complete right ICA resulting in abrupt changes in WSS. The change of posture from sleeping to standing drops the WSS in the range of 40% with a difference of 5% between both the carotids, as shown in the Fig-7.17 and according to the table-7.2. During the head-down posture change, due to higher flow rate, the WSS increases drastically by roughly six times in right carotid; while in normal left carotid, WSS rise increases by four times with sleeping position as reference as observed in the Fig-7.18. Hence, maximum wall shear at the stenosed region of right carotid will increase the thrombosis and pose risk of stroke.
7.3.3.3 Pressure

The pressure contours at peak systole in left and right carotid bifurcation are shown in the Fig-7.23 at head-down and sleeping positions, respectively. The pressure distribution pattern shows significant changes in both the carotids. The flow restriction in right ICA has elevated the pressure at the bifurcation apex extending it up to the proximal location of narrowing. It also influences in elevating the pressure in CCA proximal to bifurcation region ((Salzar et al., 1995), (Li et al., 2009)). This increased pressure profile exists till the mid diastole due to the flow restriction, while the normal left carotid bifurcation demonstrates a typical pressure profile with the maximum pressure at the bifurcation tip ((Tezduyar et al., 2008),(Cebral et al., 2011)). The left ECA is severely tortuous influencing the pressure rise when compared with right ECA, which has smaller curvature. The pressure comparison of both carotid bifurcations is plotted in the Fig-7.24 during the entire pulse cycle. Both left and right carotid demonstrates similar pressure variation for different postures.

The pressure exceeds in stenosed right carotid when compared with the normal left carotid bifurcation as noticed for various posture changes. A pressure drop of 5% is noticed during change of posture from sleeping to standing, as seen in the Fig-7.17 during peak systole. However, the pressure rises by more than 50% at peak systole during posture change from sleeping to head-down position, as observed in the Fig-7.18. Due to moderately stenosed complete ICA, the intensity of pressure build is comparatively less, as observed in severely stenosed regions. This unusual behavior is because of the nature of partial narrowing of ICA till the distal end, which diverts the additional flow into ECA, thus preventing the abrupt rise in pressure as commonly observed in high grade stenosed cases.
Fig. 7.23: Comparison of pressure contours during peak systole in case-2

Case-2: Left – Head down

Case-2: Right - Sleeping

Fig. 7.24: Pressure comparison during various postures in case-2
7.3.3.4 Wall deformation

The wall deformation distribution is shown in the Fig-7.25 at peak systole for left and right carotid at standing and head-down positions, respectively. The maximum wall deformation is found to be at the bifurcation region in both the carotids, similar to that of normal carotid bifurcation. The deformation behavior throughout the pulse cycle is similar to that as observed in the case-1. However, the variation in deformation magnitude varies due to the difference in the lumen diameter, severity of tortuous in region of bifurcation zone, ICA and ECA.

The concentric mild stenosis till the distal end of right ICA has increased the stiffness of the artery, resulting in reduced deformation of artery along the stenosed region, as observed from the Fig-7.25 ((Vavourakis et al., 2011), (Younis et al., 2004)). However, the increased pressure proximal to the entrance of stenosis remarkably increases the deformation. In contrast to the left ICA, there are no traces of arterial wall stiffening, and wall deformation is observed in the entire branch of ICA. As the flow decelerates during end diastole, complex flow in bifurcation region and carotid bulb aggravates, thereby leading to pressure drop and resulting in reduced wall deformation (Tada, Tarbell, 2005),(Zhao, 2010).

Fig-7.26 describes the wall deformation behavior of both right and left carotid bifurcation during various postures. The right carotid has higher deformation in comparison with the left carotid. Due to the mild stenosis, commonly observed shift in peak systole phase towards early diastole is absent in this case. It is noticed from the Fig-7.17 that the wall deformation drops within 5% during the change of posture from sleeping to standing.
Fig - 7.25: Comparison of wall deformation contours during peak systole in case-2

Fig - 7.26: Wall deformation comparison for various postures in case-2
Also, during postural change from sleeping to head-down position, the wall deformation increases by 30% (Fig-7.18), indicating that the change of posture alters the flow phenomenon. In both the variations, right carotid exceeds the left carotid bifurcation highlighting the influence of increased wall deformation in stenosed condition when compared with the normal condition.

7.3.3.5 Structural Stress

The von Mises stress distribution is shown in the Fig-7.27 at peak systole during head down and standing position for left and right carotid system respectively. The maximum stress is located at the bifurcation zone in both left and right carotid system. However, due to partial narrowing of entire right ICA, the entire stretch of stenosis is under very low stress and subjected to compression when compared with the left carotid. The steep gradient in stress in right carotid is more significant unlike to that observed in left carotid system. The combination low pressure, high wall shear stress and compressive von Mises stress influences the atherosclerotic progression and may be rupture (Zhao et al., 2000)(Younis et al., 2004)(Arroyo, Lee, 1999). The stress concentration factor is 2.2 and 3.75 in the apex region of left and right carotid respectively during sleeping posture.

The right carotid is having maximum stress variation and it is almost more than 40% when compared with the left carotid bifurcation as observed from the Fig-7.28 during various postures. During change of posture from sleeping to standing the drop in von Mises stress is quite less, but there is significant difference during change from sleeping to head down. The stress reduces by less than 5% during change of posture from sleeping to standing (Fig-7.17).
Fig - 7.27: Comparison of von Mises stress contours during peak systole in case-2

Fig-7.28: von Mises stress comparison for various postures in case-2
However, during posture change from sleeping to head down position, the stress in left and right carotid increases by 25% and 35% respectively (Fig-7.18). This increased value is quite different unlike to that observed in normal carotid of case-1. The presence of partial narrowing has influenced the increased pressure in upstream which is related to rise in von Mises stress considerably (Bathe, Kamm, 1999)(Tang et al., 2003). Hence, the stress pattern is more distributed and stretched in CCA when compared with the left carotid bifurcation.

7.4 Case-3: Completely occluded and partially stenosed carotid bifurcation

7.4.1 Case Description:

This peculiar stenosed carotid bifurcation case study belongs to a 60 year old male subject, who had suffered multiple strokes at different times. The left ICA is found to be completely occluded with partial narrowing, also observed at the left ECA origin as shown in the Fig-7.29[B]. On the right side, the partial narrowing of the ECA origin is observed with normal caliber of CCA and ICA (refer to Fig-7.29[A]). A 50% narrowing is diagnosed at ECA root in right carotid bifurcation, whereas a reduction of about 72% is diagnosed on the left side ECA root. Due to the complete occlusion of left ICA, the luminal caliber of left CCA has also reduced while a compensatory increase in blood flow in the left carotid system has resulted in increased luminal caliber of the right ICA and CCA.

7.4.2 3D FSI models

The grid sizes of 3D FSI models for left side carotid bifurcation consists of 33750 and 23455 hexahedral elements for fluid and solid models respectively, while the right side carotid bifurcation consists of 34220 and 21760 hexahedral elements for fluid and solid models respectively, as shown in the Fig-7.30.
Fig-7.29: Different views of CT scan of case-3: carotid bifurcation, [A] Right – partially stenosed ECA at bifurcation tip and [B] Left side - Occluded ICA and partially stenosed ECA at bifurcation tip
As observed from the carotid ultrasound Doppler, the inlet velocity into left CCA is only 25-30% of the total flow velocity due to occlusion of left ICA and partial stenosis at the root of left ECA. The reduced flow in left carotid system is compensated by increased size of right CCA with rise in 75-70% of the total flow velocity as commonly observed. Therefore, only 30% flow is applied at the inlet of left CCA, while increase in 70% of flow is applied at the inlet of right CCA. Hence appropriately reduced time varying velocity and pressure waveform is applied at inlet and outlet respectively in left carotid while increased flow pattern is adopted in the right carotid system.
7.4.3 Results and Discussion

The difference in flow variables observed at peak systole during change of postures from sleeping to head-down and sleeping to standing is presented in the table-7.3. The complete occlusion of ICA and partial narrowing at ECA root in left carotid bifurcation has altered the flow drastically in contrast to partial narrowing at ECA root in right carotid bifurcation. Even though there is less flow in left carotid system when compared with right carotid system, the higher percentage of stenosis in ECA root in the left carotid bifurcation exceeding 70% showcases the moderate risk potential for atherosclerotic changes. Although, the stenosis at right ECA has lower percentage of area reduction, the carotid system is significantly at large risk due to very high inflow (in order to compensate the left ICA occlusion) which further influences significant rise in haemodynamic variables. At peak systole, Fig-7.31 shows the percentage change in haemodynamics parameters during the change of posture from sleeping to standing, while sleeping to head-down condition is plotted, as shown in the Fig-7.32.

Table-7.3: Variation in haemodynamics parameters observed in completely occluded ICA with partial stenosis in ECA in left carotid bifurcation and partial narrowing at ECA root in right side carotid bifurcation during change of postures

<table>
<thead>
<tr>
<th>Flow variables</th>
<th>Sleeping to Standing</th>
<th>Sleeping to Head-down</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>Velocity change (m/s)</td>
<td>0.291</td>
<td>0.414</td>
</tr>
<tr>
<td>WSS change (Pa)</td>
<td>2.940</td>
<td>3.923</td>
</tr>
<tr>
<td>Pressure change (Pa)</td>
<td>241</td>
<td>342</td>
</tr>
<tr>
<td>Wall deformation change (mm)</td>
<td>0.012</td>
<td>0.046</td>
</tr>
<tr>
<td>Von mises stress (Pa)</td>
<td>2540</td>
<td>4376</td>
</tr>
</tbody>
</table>
Fig-7.31: Percentage variation during change of posture from sleeping to standing - Case: 3

Fig-7.32: Percentage variation during change of posture from sleeping to head-down - Case: 3
The mild occlusion in the right carotid bifurcation has influenced a sufficiently large variation in pressure, wall deformation and WSS when compared with the left side, as observed from both these plots. Moreover, the mild variation is noticed in the velocity during the change from sleeping to head down in comparison with the change from sleeping to standing.

7.4.3.1 Velocity

Fig-7.33 illustrates the velocity streamlines at peak systole during the standing position, in left and right carotid bifurcation. Despite mild narrowing at root of ECA in right carotid bifurcation, ICA has higher flow distribution in than in ECA without affecting the complexity in flow similar to that observed in typical carotid bifurcation. In right carotid bifurcation, the maximum velocity is observed to be in inner wall of ICA with partial increase at throat region of stenosis at ECA root. The maximum velocity in left carotid bifurcation is observed at the root of ECA with severe stenosis.

The complete occlusion of left ICA itself has reduced incoming flow through left ECA. However, the severe narrowing at left ECA root has further disturbed the velocity with stronger flow separation at distal side ((Deshpande et al., 2009), (Marshall et al., 2004), (Leach et al., 2010)). During the latter part of the pulse cycle, complexity increases with elevated disturbed flow separation and intense vortex formations along the distal side of ECA, in the left carotid bifurcation. However, the moderate narrowing at ECA root in the right carotid bifurcation has reduced the flow disturbance without major changes even in the latter part of the pulse cycle (Rayz et al., 2008).
Fig-7.33: Comparison of velocity streamlines during peak systole in case-3

Fig-7.34: Maximum velocity comparison for various postures in case-3
The flow changes at the right bifurcation region and right ICA demonstrates the typical flow, as observed in typical normal carotid bifurcation. The complete occlusion of ICA in left carotid system has resulted in decreased lumen diameter of CCA and ECA, but constant flow to head and neck region is compensated through the increased lumen diameter of CCA and ICA of the right carotid bifurcation. The flow changes observed during various positions in right and left carotid bifurcation are plotted in the Fig-7.34. The maximum inflow into right carotid system when compared with left carotid has influenced the considerable broadening of peak systole phase with longer delay in the flow deceleration for all the postures in right carotid bifurcation.

Further, the variation in magnitude of flow velocity also shows the elevated velocities in right carotid than left carotid bifurcation, as mentioned in the table-7.3. The percentage variation of flow velocity during the change of posture from sleeping to standing indicates a drop in 30-35%, as observed in the Fig -7.31, while the velocity increases by three times during the change from sleeping to head-down position, as seen in Fig-7.32.

7.4.3.2 Wall Shear Stress

Fig-7.35 shows WSS contours at peak systole in left and right carotid system during the sleeping and the head-down positions respectively. WSS in the right ECA at the throat of stenosis, close to bifurcation apex is found to have quite high WSS, while the maximum value is noticed towards the inner wall of the right ICA extending till the distal end. The bifurcation zone and the inner wall of right ECA at post-stenotic zone towards the distal side also have fairly low WSS distribution unlike right CCA distribution (Aars and Soldberg, 1971).
Fig-7.35: Comparison of wall shear stress contours during peak systole in case-3

Fig-7.36: Wall shear stress comparison for various postures in case-3
Initial complete occlusion of left ICA has slightly increased the lumen size of left ECA to compensate the flow in the downstream side and the partial narrowing at the root of the left ECA at later stage has further altered the flow behavior abruptly, resulting in drastic rise of WSS at the stenosis. The low flow zones in quite less in right carotid due to high flow rate. However, inner wall of ECA and at the bifurcation zone have traces of very low wall shear stress (>2Pa) and shall slightly reduce the influence of atherosclerosis progression (Malek, Alper, 1999). In left carotid, the flow recirculation is covered by CCA and intense flow separation region in proximal side of ECA root stenosis. In these region, the extremely low shear stress (>0.4Pa) shall induce the atherosclerosis progression ((Lee et al., 2013) (Deshpande, 2009) (Leach et al., 2010)).

Even though there is high flow rate in right carotid system than left carotid bifurcation, the maximum WSS at throat of stenosis in right carotid system is slightly on higher side unlike to that observed in left carotid system (Long et al., 2001). Also, severe multiple stenosis have further induced the abrupt flow disturbance with highly complex vortex formation in downstream of partial narrowing in left ECA. The helical flow induced in the downstream is highly complex and extends till the distal end of left ECA and prominent till the latter part of the pulse cycle. The flow variation is compared in the Fig-7.36 in both the normal and stenosed carotid systems during the entire pulse cycle for various postures. The WSS in both left and right carotid system substantially drops by 50% with slightly higher variation in right carotid than left carotid during the change of posture from sleeping to standing (Fig-7.31). The change to head-down position drastically increases the WSS in the left and right carotid by six and five times respectively (Fig-7.32). The high WSS
variation during the change of postures will certainly trigger the damage to arterial wall and induce the plaque rupture (Ku, 1997). The clinical implications of high WSS is such that it will further stimulate the platelet thrombosis and result in total occlusion of the vessel especially in left ECA root, severely damaging the endothelial cells ((Molla, 2009), (Cecchi et al., 2011)).

7.4.3.3 Pressure

Fig-7.37 shows the pressure distribution at peak systole in left and right carotid bifurcations during sleeping and head-down positions respectively. The pressure profile in right carotid bifurcation with partial narrowing at ECA root highlights maximum pressure at bifurcation apex covering lesser area when compared with typical normal carotid bifurcation in case-1. At the maximum stenosed region, the pressure drops consistently throughout the pulse cycle and further increases again in the distal end of right ECA. The minor pressure drop is not significant as compared with the commonly observed high grade stenosis.

The pressure pattern remains similar in both right and left CCA throughout the pulse cycle without any major variations. The outer wall of the right ICA has a pressure rise due to the flow separation resulting in velocity drop, unlike towards the inner wall where there is an increase in flow velocity resulting in the pressure drop (Cebral et al., 2001). The complete occlusion of the left ICA has considerably altered pressure behavior in the left carotid bifurcation when compared with the normal carotid bifurcation on the right side. Due to flow compensation on the right carotid side, the pressure behavior is considerably higher when compared with the left carotid system, with considerably very low pressure formation as observed in the severe stenosis at root of left ECA.
Fig. 7.37: Comparison of pressure contours during peak systole in case-3

Case-3: Right – Sleeping

Case-3: Left – Head down

Fig-7.38: Pressure comparison during various postures in case-3
Meanwhile, the significant pressure drop at the throat of stenosis in left carotid, much below the external pressure, can trigger atherosclerotic causing damage to the arterial wall ((Li et al., 2009),(Salzar et al., 1995), (Mohammed Abdul Hye, 2012)). The immediate distal side at the throat of stenosis in the left ECA is severely tortuous inducing the pressure rise. Fig-7.38 shows the difference in pressure between left and right carotid bifurcations, during various postural changes throughout the pulse cycle. The right carotid bifurcation behavior demonstrates slightly higher pressure rise as compared with typical normal carotid bifurcation pressure behavior during sleeping and standing postures, but significant increase during head down because of the partial narrowing in the ECA and high inflow into right CCA. The pressure distribution in left carotid has reduced considerably by more than 60% to that of typically observed physiological pressure in sleeping and standing postures. However, during head down pressure it increases marginally closer to the actual physiological pressure.

The right carotid bifurcation has escalated the pressure to large values when compared with the left carotid bifurcation. The peak systole phase of pulse cycle in right carotid has a slight shift towards the mid-diastole when compared with the left carotid system. The higher inflow into right CCA to compensate the flow in left CCA and time required for flow stabilization has resulted in the peak systole time delay. This in turn has also influenced the delayed flow response during flow acceleration and deceleration resulting in delaying the time required for accumulated pressure to drop proximal to the throat of stenosis. The pressure reduces by 5% and 15% in left carotid and right carotid bifurcations respectively, during posture change from sleeping to standing, as seen in the Fig-7.31. During the postural change from
sleeping to head-down position, the pressure rises by 25% in left carotid, while in the case of right carotid it increases by more than 50% (Fig-7.32). As discussed in chapter-5, these theoretically large pressure drops may have severe impact on the pathophysiology of the artery, potentially resulting in significant flow reduction. In actual physiological conditions, this unphysiological pressure drop and rise in normal and severely stenosed carotid bifurcation may not be completely and effectively corrected by cerebral auto-regulation. From the observed results, it is advised that the patient should avoid standing position for long duration as subsequent pressure drop at the stenosis site can induce the plaque rupture. Head down position adopted during yogic postures is also not advised as large pressure build up proximal to plaque can complicate the atherosclerosis.

7.4.3.4 Wall deformation

The maximum wall deformation contours at peak systole in right and left carotid bifurcations is shown in the Fig-7.39 during head-down and sleeping postures respectively. In the right carotid bifurcation, the maximum wall deformation is observed to be at the bifurcation region, alike normal carotid bifurcation deformation behavior. The plaque formation at the mild eccentric stenosis at the right ECA root has increased the stiffness of surrounding arterial wall resulting in reduced elastic wall deformation. Since the intensity of reduced wall stiffness is localized, surrounding the ECA root region alone, it results in reduced wall deformation at the stenosed location distributed across smaller area ((Younis et al., 2004), (Cho et al., 2011)). Another interesting observation is the post-stenotic deformation in distal side of the right ECA because of the eccentric stenosis. However, the post-stenotic deformation has lower profile due to increased stiffness of the plaque formation (Tang et al., 1999b).
Fig-7.39: Comparison of wall deformation contours during peak systole in case-3

Fig-7.40: Wall deformation comparison for various postures in case-3
Therefore, the partial restriction offered for the flow in right ECA diverts the major part of the flow through right ICA. However, the increased pressure in upstream of mild narrowing to compensate the flow has escalated the deformation distribution. Hence, the maximum deformation is found to be at peak systole at the entrance region of ICA in the bifurcation region. The complete occlusion of left ICA and severe eccentric stenosed left ECA root has restricted the major part of the flow through left carotid bifurcation. More than 70% stenosis at the left ECA root has significantly reduced the stiffness of plaque formation and surrounding arterial wall, resulting in substantial reduction of wall deformation, as observed from the Fig-7.39. Further, this flow restriction has influenced the considerable rise in pressure profile in proximity to the bifurcation region in CCA, resulting in instant increase in wall deformation. Hence, left carotid has maximum deformation towards outer wall of CCA in posterior view as seen in the Fig-7.39.

Fig-7.40 compares the variation in wall deformation in different postures in both the carotids throughout the pulse cycle. The right carotid wall deformation variation, because of mild partial eccentric stenosis, is found to be similar to the commonly observed deformation behavior of typical normal carotid bifurcation ((Toloui et al., 2012),(Gao, 2010b)). The high inflow and partial stenosis at the root of right ECA has slightly shifted the deformation profile at peak systole towards mid diastole, as typically observed in stenotic wall deformation. Due to very less flow in left carotid system, the deformation has considerably reduced unlike the right carotid system. This reduced deformation further influences in increasing the stiffness of the left carotid bifurcation thereby losing it elastic property. During the change of posture from sleeping to standing, the deformation value drops by 8% and 15% in
left and right carotids respectively, as shown in the Fig-7.31. The percentage variation in the wall deformation during the change in posture from sleeping to head-down has significantly altered the wall deformation pattern. The deformation value rises by 40% in left carotid; while in the right carotid it is almost twice (Fig-7.32). This unusual behavior is at high risk factor since high wall deformation in the left carotid during postural change can trigger the plaque rupture. The reduced deformation value in the right carotid is also of prime concern as arterial wall is gradually losing its elasticity due to increased stiffness, resulting in less pulsatile behavior (Tang et al., 2004). The high pressure in upstream of stenosis causes the maximum wall deformation and the intense pressure drop at the throat region will result in wall collapse (Tang et al.(2004). Also, the maximum pressure will alter the mechanical forces close to stenosis and increasing the plaque rupture ((Lee, Xu, 2002), (Arroyo, Lee, 1999), (Binns, Ku, 1989)). Moreover, with increase of severity of stenosis, arterial wall stiffness increases and further influences the atherosclerosis ((Cecelja, Chowienczyk, 2012)(Kozlov et al., 2012)).

7.4.3.5 Structural stress

The maximum von mises stress at peak systole is observed to be at the bifurcation zone in right carotid and in CCA proximal to bifurcation apex in left carotid system as shown in the Fig-7.41. The high inflow in right CCA unlike very less flow into left CCA and geometry of both the carotids has altered the stress distribution significantly. In the right carotid bifurcation the maximum stress distribution is along the bifurcation region with moderate stress gradients in outer wall of ICA and ECA. Due to partial stenosis at ECA root, the flow is altered in downstream side and has influenced the quite high stress gradients due to pressure loads unlike normal ICA ((Perktold, Rappitsch, 1995)(Arroyo, Lee, 1999) (Younis et al., 2004)).
Fig - 7.41: Comparison of von Mises stress contours during peak systole in case-3

Fig-7.42: von Mises stress comparison for various postures in case-3
In the left carotid system, the flow is completely reduced into CCA and ECA due to complete occlusion of ICA. In addition to the severe stenosis at the ECA root, the pressure build up proximal to bifurcation region has results in maximum stress distribution in the CCA close to the bifurcation apex. Also, the flow in distal side has further influenced the moderate stress gradient. At the stenosis throat, the left ECA is subjected to very high compression despite reduced inflow from CCA unlike moderate compression in right ECA with high inflow from CCA. The intense pressure drop and compressive stresses in left ECA root will further induce the atherosclerotic progression and alter the mechanical forces onto plaque site (Lee et al., 2004)(Binns, Ku, 1989)(Leach et al., 2010). The stress concentration factor is 25.3 and 3.26 in the bifurcation zone of left and right carotid respectively during sleeping posture, thus indicating the high risk factor (Gao, 2010)(Perktold, Rappitsch, 1995).

Fig-7.42 compares the variation of von Mises stress during different postures. It is observed that right carotid has more than 75% variation when compared with left carotid system. The stress variation during change of posture from sleeping to standing is slightly less when compared to changes during change from sleeping to head down in both the carotids. During change of posture from sleeping to standing, the stress drops by 5% and 15% in left and right carotid system as shown in the Fig-7.31. However, the stress increases by more than 20% in left carotid and more than 50% in right carotid system (Fig-7.32). Even though the stress value is extremely less in left carotid unlike the right carotid, but increased compressive in the stenosed region highly influences the plaque progression or even rupture. The severe stenosis in left carotid has increased the pressure in upstream resulting in
considerably large distribution of stress in the left CCA unlike the right carotid which is intense more locally at the bifurcation apex.

7.5 Case-4:

7.5.1 Case Description:

Case-4 is taken from a 58 year old female patient who presented with a hemorrhagic stroke (sudden subarachnoid hemorrhage due to aneurysmal rupture), a broad necked aneurysm is observed arising from the bifurcation of left ICA, while the right ICA bifurcation appears to be normal. The location of the broad neck aneurysm and normal ICA bifurcation is highlighted in three different views, as shown in the Fig-7.43[B] and [A] respectively.

7.5.2 3D FSI Models:

The grid sizes of 3D FSI models for left side carotid bifurcation consists of 35230 and 21270 hexahedral elements for fluid and solid models respectively; while the right side carotid bifurcation consists of 36480 and 22450 hexahedral elements for fluid and solid models respectively, as shown in the Fig-7.44. The velocity obtained from carotid Doppler at ICA is applied as time varying velocity waveform at the inlet and pulsatile pressure waveform similar to that of case-1 and 2 is applied at the outlet in both aneurysm and normal ICA bifurcation models.

![Fig-7.44: Case-4 Carotid bifurcation FSI models (Left and right side)](image)

Left side has giant aneurysm at ICA bifurcation and Right side is normal
Fig-7.43: Different views of CT scan of case-4: ICA bifurcation,
[A] Right - normal and [B] Left side - giant aneurysm
7.5.3 Results and Discussion:

The changes in the flow behavior observed at peak systole are depicted in the table-7.4 during the change of different postures. The flow variables in left ICA bifurcation with aneurysm are higher when compared with that of normal ICA bifurcation on the right side.

Table-7.4: Variation in haemodynamics parameters observed in aneurysm and normal side ICA bifurcation during change of postures

<table>
<thead>
<tr>
<th>Flow variables</th>
<th>Sleeping to Standing</th>
<th>Sleeping to Head-down</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>Velocity change (m/s)</td>
<td>0.455</td>
<td>0.265</td>
</tr>
<tr>
<td>WSS change (Pa)</td>
<td>10.217</td>
<td>2.809</td>
</tr>
<tr>
<td>Pressure change (Pa)</td>
<td>890.58</td>
<td>330.08</td>
</tr>
<tr>
<td>Wall deformation change (mm)</td>
<td>0.113</td>
<td>0.020</td>
</tr>
<tr>
<td>Von mises stress (Pa)</td>
<td>13079</td>
<td>91396</td>
</tr>
</tbody>
</table>

The aneurysm side has very large pressure variation in contrast to normal side during the change of posture from sleeping to head-down position when compared to the change from sleeping to standing. The percentage variation of these flow variables also shows the similar characteristics as that of table and also depicted in the Figs-7.45 and 7.46. Compared to the pressure, the velocity variation in addition to WSS and wall deformation in normal side has higher percentage change than the aneurysm side. The differences in the flow behavior are described individually in the subsequent sections.
Fig-7.45: Percentage variation during change of posture from sleeping to standing - Case: 4

Fig-7.46: Percentage variation during change of posture from sleeping to head-down - Case: 4
7.5.3.1 Velocity

Velocity streamlines of normal and aneurysm ICA bifurcation are described in the Fig-7.47 during peak systole for head-down and standing postures, respectively. In the normal ICA bifurcation, the upstream of bifurcation has intense flow velocity, which impinges on the arterial wall and reduces at the bifurcation tip due to the flow distribution and further stabilizes in the downstream end in MCA and ACA. In aneurysm side, the flow velocity enters the dome at higher velocity as seen in anterior view (A), swirls in the sac and exits as seen in posterior view (P). The velocity will be stagnant at the core of the sac, as the complete flow exit chances are less due to the pulsatile nature of flow ((Cebral et al., 2009), (Takizawa et al., 2011)).

The flow in downstream end of aneurysm side is highly intense and disturbed with majority of flow entering the MCA as compared with ACA, in contrast to normal ICA bifurcation (Torii et al., 2009). The high flow velocity entering the sac of aneurysm elongates the dome towards the apex. Thus, the higher velocity is observed in aneurysm case than in the normal case, for various postures. The velocity behavior compared during the various postures are shown in the Fig -7.48.

The flow velocity decreases by 30% with minor difference between normal and aneurysm models during the change of posture from sleeping to standing (Fig-7.45), while the change of posture from sleeping to head-down has a significantly larger increase, as observed in the Fig-7.46. The flow swirling increases in head-down position, causing increase in sac pressure and enlargement of the sac with larger region of flow recirculation (Mohammed Abdul Hye, 2012).
Fig-7.47: Comparison of velocity streamlines during peak systole in case-4

Fig-7.48: Maximum velocity comparison for various postures in case-4
Pathologically, these large recirculation zones are dangerous as they increase the blood residence time and may induce blood clot or thrombus formation inside the aneurysm (Rayz et al., 2008). The newly formed fragile blood clots may exit the aneurysm with potential risk of embolic stroke further downstream.

7.5.3.2 Wall Shear Stress

The most interesting haemodynamic parameter in relation to the aneurysm progression is the WSS which varies due to the pulsatile nature of the flow. The maximum value generally occurs at the peak systole, when the inflow is maximum. The WSS distribution is found to be more at the normal ICA bifurcation region, especially along the outer wall of MCA and ACA, as shown in the Fig-7.49, during peak systole. WSS reduces at the bifurcation tip, since the velocity is less due to the flow jet from ICA impinging at the bifurcation tip region, thus reducing the flow. The WSS distribution in ICA aneurysm is the highest at the neck region and the lowest in the dome region. The entry region of the sac has maximum distribution of WSS where the flow is the highest, especially at the neck region of the sac, and later as the flow reduces towards the exit side of the sac, WSS also drops gradually.

The range of WSS in the dome is relatively less and within the lower limit of physiological WSS range (Torii et al., 2009). This lower range of WSS located near the apex may also play an important role in aneurysm rupture through degradation of the aneurysmal wall because of the abnormal metabolic activity in arterial wall and aggregation of inflammatory cells in the region due to relative flow stasis (Meng et al., 2014). This separate mechanism of endothelial injury in areas of low WSS also has the potential to cause further atherosclerotic disease progression (Lasheras, 2007).
Fig-7.49: Comparison of wall shear stress contours during peak systole in case-4

Case-4: Right – Sleeping

Case-4: Left – Sleeping

Fig-7.50: Wall shear stress comparison for various postures in case-4
Another interest to note is that high WSS near the neck of sac results in lamina loss, media thinning and bulge formation, thus initiating the aneurysm formation. The initial enlargement of aneurysmal bulge results in flow recirculation within the sac and thus the flow behavior is dominated by low WSS. The low WSS will further lead to wall inflammation and accentuate thrombus formation (Ku, 1997), (Jeong, Rhee, 2012), (Salsac et al., 2004). Moreover, the maximum WSS is observed to be in aneurysm case than in normal ICA bifurcation, as shown in the Fig- 7.50. The flow jet at the tip of normal ICA bifurcation is more intense in head down position than in standing or sleeping positions.

In aneurysm case, the sac filling is more intense in head down position than in standing or sleeping positions. WSS is distributed to nearly half of the dome in supine and standing positions, but in the head down position, it covers almost the entire dome region. Due to the presence of aneurysmal sac, there is a large difference in flow parameters compared to normal bifurcation. The change of posture from sleeping to standing reduces the WSS by 35% and 45% in normal ICA and ICA aneurysms, respectively (Fig-7.45).

In head-down position, WSS increases by ten times in aneurysm ICA and three times in normal ICA bifurcation, as noticed in the Fig-7.46. Thus, the head-down position (or any other cause of increased flow / pressure) should be avoided, because the sudden increase in WSS and higher sac pressure may accentuate the risk of aneurysm rupture and accelerate the atherosclerotic disease progression.
7.5.3.3 Pressure

The pressure distribution in aneurysm ICA bifurcation is higher than in normal ICA bifurcation. In normal side, the pressure at the bifurcation tip rises as the flow velocity dips and distributes into MCA and ACA. In case of aneurysm ICA bifurcation, the entry side of the dome is subjected to higher pressure when compared with the rest of the dome as shown in the Fig-7.51. The large pressure within the sac influences the inflation of sac towards apex ((Torii et al., 2008, 2009), (Mohammed Abdul Hye, 2012)). The flow entry of aneurysm can be seen in the posterior view (P) with larger patch of higher pressure than the rest of the dome, as observed in anterior view (A). Fig-7.52 compares the normal and aneurysm ICA bifurcation pressure variations for different postures.

During the head-down position, the aneurysm side experiences maximum pressure than the normal side. Even for other postures like standing and sleeping, aneurysm side has higher pressure than compared with normal side. During the change of posture from sleeping to standing during peak systole, the pressure drops by 5% and 12% in normal and aneurysm ICA bifurcation, as observed in the Fig-7.45, and also from the table-7.4. During the change of posture from sleeping to head-down, the pressure increases by 80% and 50% in aneurysm and normal ICA bifurcation, according to the Fig-7.46.

7.5.3.4 Wall deformation

Fig-7.53 shows the wall deformation during peak systole in normal and aneurysm ICA bifurcation. In the normal side, the maximum deformation is observed to be at the bifurcation tip, which has the higher pressure distribution (Torii et al., 2009). Because of the broad neck aneurysm, the flow jet directly hits the apex, and most of the blood flow at the center of the sac is almost stagnant.
Fig-7.51: Comparison of pressure contours during peak systole in case-4

Case-4: Right – Head down

Case-4: Left – Sleeping

Fig-7.52: Pressure comparison during various postures in case-4
Hence, the entire sac is subjected to higher pressure; the apex region, including the entry side of dome experiences maximum deformation, and gradually decreases towards the neck region ((Isaksen et al., 2008), (Bazilevs et al., 2010)). The aneurysm side has maximum deformation in contrast to the normal side ICA bifurcation. The wall deformation is compared for various postures, as shown in the Fig-7.54. The maximum deformation decreases by 10% and 7% during the change of posture from sleeping to standing in aneurysm and normal sides, respectively, as observed in Fig-7.45. But there is a significant rise during the change of posture from sleeping to head-down in contrast to that of standing with a major difference of 25% between normal and aneurysm sides as depicted in Fig-7.46.

7.5.3.5 Structural stress

The von Mises stress is shown at peak systole in Fig-7.55 in right and left ICA bifurcation during sleeping position. In normal ICA bifurcation, the maximum stress is found to be at the bifurcation tip which has relatively higher pressure (Ku et al., 1985). Also moderately less stress is found to be distributed ICA and MCA unlike ACA. In case of broad neck aneurysm, higher pressure load allows for the deformation of entire sac resulting in the intense stretching of the dome about the neck (Yahya, 2010) (Valencia, Solis, 2006). Hence, this stretching of the dome neck causes the maximum stress especially at the entry side of the dome as observed in posterior and anterior views (Fig-7.55)(Castro, 2013). The stress concentration factor in normal and aneurysm ICA bifurcation is found to be 2.92 and 4.80 respectively. The variation of von Mises stress in both normal and aneurysm side is shown in the Fig-7.56. The right side aneurysm ICA bifurcation has higher stress variation when compared with the left side normal ICA bifurcation.
Fig-7.53: Comparison of wall deformation contours during peak systole in case-4

Fig-7.54: Wall deformation comparison for various postures in case-4
Fig - 7.55: Comparison of von Mises stress contours during peak systole in case-4

Fig-7.56: von Mises stress comparison for various postures in case-4
During change of posture from sleeping to standing, the maximum stress drops by 70% in aneurysm side and 10% in normal side as shown in the Fig-7.45. Moreover, the maximum stress increases by 2.5% and 25% in normal and aneurysm ICA bifurcation respectively (Fig-7.46).

**7.6 Concluding remarks:**

The present investigation highlights the significant changes in the flow behavior in various subject specific cases in different postures, with supine posture as reference. Flow behavior is compared in four cases ranging from normal carotid bifurcation, partial and complete arterial stenosis, and ICA bifurcation aneurism. It provides a very good comparison of haemodynamic changes, under different categories of normal and diseased states. The obtained results indicate severe and considerable changes in head-down position as compared with minor variations in standing position with reference to sleeping position. Haemodynamic parameters such as WSS, pressure, flow velocity, arterial wall deformation and von Mises stress are investigated individually in all the cases. When compared with the rest of these flow parameters, WSS is found to have the most significant variation during postural changes. During the sleeping posture, the flow parameters in all cases agreed well with the values from literature and clinical observations.

The normal left and right carotid bifurcations are discussed in case-1. Even though both carotids are normal without any evidence of atherosclerosis, minor variations between the two sides are noticed because of different geometry. Even during head-down position, pressure variation and wall deformation showed a steady rise of 20% in contrast to less than 5% drop while standing, but velocity and WSS
showed considerable and abrupt changes during standing and head-down position. The skewed geometry in both carotids has the potential to increase the flow separation and low flow zone at bifurcation region can aggravate the atherosclerotic progression.

Case-2 is a combination of normal and partially narrowed carotid bifurcation. The right ICA is partially narrowed, while the rest of the carotid system is diagnosed to be normal. The flow restriction offered by the partial stenosis has considerably affected the flow in downstream side. However, due to mild narrowing (less than 70%), clinically it is termed to be less significant with low risk factor. From the investigation carried out during different postures, substantially large variation is observed in right carotid in contrast to the left carotid system. The partial narrowing has reduced the arterial wall stiffness (due to increased pressure) and increased the arterial wall deformation.

The increased WSS in the region of maximum stenosis has the large risk of atherosclerotic plaque rupture. The low wall shear stress at the bifurcation is found to be more in right carotid than the left carotid highlighting the region is prone to atherosclerosis progression. The large variation in pressure in turn increases the wall deformation, which affects the stiffness of the arterial wall. The arterial wall becomes stiffer with the increased severity of stenosis (Tang et al., 1999a). Severe stenosis will increase the pressure and in turn increasing the arterial wall stiffness according to (Cecelja, Chowienczyk, 2012)(Kozlov et al., 2012). The risk factor associated is quite high in the right carotid than the left carotid system.
Case-3 is a unique one with complete occlusion of left ICA, 50% stenosis of right ECA root (no risk as no contribution to cerebral circulation) and 70% stenosis of right ICA root (high risk for haemodynamic changes). The inflow is higher in right carotid than the left carotid system due to flow compensation from completely occluded left ICA. Multiple severe occlusions in the left carotid has significantly altered the flow behavior (especially with low wall shear stress, increased compression of stenosis at the left ECA root), when compared with the right side inspite of maximum flow.

The increased WSS at the throat of left ECA stenosis will further induce thrombosis and total occlusion and sudden pressure drop will stimulate the plaque rupture. However, increase in the lumen of right carotid system compensates for the restricted flow in the left carotid system. The pressure drop and moderately higher WSS at the level of maximum stenosis marginally reduces the arterial wall stiffness resulting in low risk factor of disease progression.

Case-4 evaluates an aneurysm at left ICA bifurcation, while the right ICA bifurcation appears normal without any aneurysm formation. Flow haemodynamics are highly turbulent and complex in an aneurysm, unlike the normal right ICA bifurcation. High value of WSS at the neck of aneurysm and corresponding low levels at the apex will induce thrombus formation, while the complex swirling flow and increased pressure in the dome increases the risk of rupture. The maximum von Mises stress observed at the neck of aneurysm also influences the aneurysm rupture. The normal ICA bifurcation demonstrates the typical flow pattern as observed clinically with mild flow separation and increased pressure at the point of bifurcation.
Marginal increase in WSS closer to the point of bifurcation is also observed (one of the reasons for aneurysm formation). Since the bifurcation zone is subjected to high pressure and WSS which allows for internal lamina damage and promoting sac formation Meng H et al.(2013) and Foutrakis G.N et al.(1999).

In the real life conditions, cerebral auto-regulation rapidly corrects pressure fall (standing being a physiological position in humans) and actual pressure falls are probably insignificant. However, in patients with stroke (particularly ischemic stroke or infarction), cerebral auto regulation and reserve is usually impaired. The postural pressure drop may be large enough to exceed the physiological threshold and lead to symptoms. It is clearly noted from the numerical simulations of subject-specific cases that normal and healthy people undergoing different postural changes in day-to-day life are the least affected as flow variables are within their physiological limits.

However, patients suffering from haemodynamically significant atherosclerotic disease, particularly arterial stenosis, may benefit from avoiding standing posture for long durations or any other condition that induces significant hypotension (Aaslid et al. (1988), Greene and Lee et al.(2012), Krause et al.(2000)). Similarly, such patients should also avoid the head-down posture as it can aggravate flow responses with high WSS, pressure build-up, reduced wall stiffness across the stenosis, increased compressive stresses in the plaque, which can trigger plaque rupture or induce thrombosis formation. It is also clearly observed from the subject specific geometric models the usefulness of FSI over rigid wall simulation, which can provide the detailed insight in investigating the haemodynamics in normal and diseased
conditions through simulations, which otherwise is not possible with the current imaging diagnostic modalities. The basic theme of this investigation is to observe the variations in the flow behavior under the influence of different postures and to provide the basis for further studies associated with treatment planning and to be used as a diagnostic tool.