Rupture Mechanism of Cerebral Carotid Aneurysm Using Computational Methods

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Abstract

This study helps to predict the rupture mechanism of an Inter Carotid Artery (ICA) for saccular aneurysm study through the Finite Element Method (FEM) combined with Discrete Element Method (DEM) of LS DYNA and also compared with a Fluid Solid Interaction (FSI) study. Also the thickness of an artery wall was found by using James-Guth Stress Strain Relation with validation. It was concluded that the Finite Element Method with Discrete Element Method was more efficient than FSI as the computation time was reduced by 51.55% with an error of 0.08%.

Keywords: discrete element method (DEM); James-Guth stress strain relation; fluid solid interaction (FSI); internal carotid artery (ICA); saccular aneurysm; rupture mechanism ; finite element method (FEM)

1. Introduction

An aneurysm is a localized inflation of an artery due to various factors such as stress, smoking, drug abuse and trauma etc. It’s one among the cerebral vascular disorder. Ignorance to it may cause hemorrhage and might even prove to be fatal. There are three types of aneurysm shown in Figure 1 as saccular, fusiform and berry. Also they are classified based on the diameter of the aneurysm as small, medium and large aneurysms. Takato Morioka et.al. (1949) proved that the odds of predicting the existence of aneurysm based on the symptoms are very slim. Based on the previous analyzed data, from all the patients examined, two third of the patient failed to show any symptoms at all. But not only predicting the presence of an aneurysm is important but also it is equally important to estimate its failure criteria. Hence understanding the rupture mechanism of an aneurysm is of at most important. Many patients live long normally even though an aneurysm exist in their body as the rate of aneurysm inflation is very slow, but this statement can be contradicted based on the past cases encountered by the doctors in which the inflation rate has amplified and ultimately causing death of the patient due to hemorrhage.
Many studies have been conducted in the past like Joseph F. Polak et.al. (1999) in order to understand the rupture mechanism of an aneurysm and also to predict its failure criteria. An orthodox method of doing so is by taking a CT scan or a MRI of a patient and based on its dimensional specifications various parameters are found and these parameters have a tolerance limit which is decided from past experiments and theoretical studies. Parameter such as intima media thickness, Wall Shears Stress & Aspect Ratio etc. There are many other parameters related to hemodynamic study but in this study we will be concerned with the above mentioned parameters.

Knowing the significance and precision of the results obtained from the CAE analysis, various CFD based studies have been conducted in the past. Chien et al (2009) conducted similar such hemodynamic study on an internal carotid artery-ophthalmic artery aneurysm. It was observed that aneurysm having more complex flow pattern in the aneurysm were more prone to rupture. Also in the rupture aneurysm the WSS distribution was comparatively more homogeneous then the unruptured ones. Another such similar analysis was done on a giant internal carotid artery aneurysm. The motive of this study was to use CFD approach to analyze the surgical management along with is clinical course of a giant carotid aneurysm. For this the two models were analyzed which were taken before and after the treatment. A CFD analysis was conducted on both the models to simulate the flow and the WSS distribution. It was observed that the hemodynamic features have improved than the previous intervention, thus concluded that CFD study to be helpful in such cases which were similar to Russin et al (2015).

Literature review shows that most of the studies have used CFD approach in order to carry out analysis related to rupture mechanism Feng et al (2007) have also conducted such studies.
Also, there is less literature available on numerical study of internal carotid artery (ICA). Also the CFD studies takes high computational time and hence taking in to account all the above factors it was decided to study the rupture mechanism of ICA using computational methods as a topic of our study.

![Figure 2 Anatomy of Carotid Artery](image)

In this study aneurysm of internal carotid artery saccular aneurysms considered. The anatomy of carotid artery is given in Figure 2. Although the previous studies done on aneurysm rupture were convincing but there was limited approach to do the study. Use of CAE in the aneurysm study reduced the error caused by humans and also aids to draw a relevant inference based on the flow simulation obtained from a CFD study which would be more precise. But this approach has a significant drawback of large computation time and it follows the frequently used CFD approach to obtain sound results, hence the approach to do the rupture mechanism study was limited. The motive of this study was to find an alternative computationally efficient approach to simulate and analyze rupture mechanism of ICA. Finite Element Method coupled with Discrete Element Method has been a new field of study in the recent times and due to its ability to obtain appropriate solution in fewer periods of time then the Finite Element Method which has been a trend from a very long time in studying various aspects using CAE approach, FEM/DEM has been an alternative approach used in this study. Displacement and other parameters will be obtained from FEM but it will not be enough to replace unless this method facilitates flow simulation. Hence in order to accomplish this limitation it was combined with the Discrete Element Method which would be responsible for flow simulation of the blood. The
key aspect of this study was to simulate the flow of blood in the form of particles. Russin et al (2015) proved that it helps to predict the complex flow inside the aneurysm which will in turn be helpful for predicting the effectiveness of treatments on a patient possessing ICA.

This method to study rupture mechanism of an ICA needs validation, and that would be achieved by the convention method involved in the CAE method which would be CFD approach (Fluid Solid Interaction model). Stress parameter obtained by both the approaches would be compared and the precision would be checked. Based on this the credibility of the new rupture mechanism study approach would be tested and concluded. An additional objective of this study was to find the algorithm to find the thickness of the aneurysm at various stages, right from the time of its formation till its rupture.

2. Methodology

The analysis for the rupture mechanism consisted of two fundamental approaches Finite Element Method (FEM) and Discrete Element Method (DEM). The motive of using these approaches was to reduce computation time for the analysis and to simulate the pulsating flow of blood without performing any CFD (FSI) analysis. This need of computation time reduction can be achieved by the use of high-performance system but that will prove to be expensive. Another alternative method to achieve this would be by reducing the number of elements involved in the simulation. FEM would not serve the purpose as the mesh involved in the CFD study would be volume mesh. But on the contrary FEM/DEM needs the 2D mesh. And the utilization of the DEM would reduce the elements used to model the fluid and the aid to simulate the flow would also be achieved which could replace the FSI study or prove to be an alternative with less computation time. More specifically this method would be more helpful where only the structural parameters would be of more significance.

The aneurysm considered in our study is an Internal Carotid Artery aneurysm; it is classified as a small aneurysm as its diameter is 8.1 mm and its type is saccular. The aneurysm is having an aspect ratio of 1.5, height ratio of 1.2 and an inflow angle of 850. Table 1 consists the specifications of the ICA. A subsection

Table 1 Specification of Blood and Artery Wall
| Parameter               | Units                   | Value                      |
|-------------------------|-------------------------|----------------------------|
| **Blood**               |                         |                            |
| Density (kg/m³)         |                         | 1100                       |
| Specific Heat (J/kg-K)  |                         | 4186                       |
| Reynolds Number         |                         | 176 (laminar flow)         |
| **Artery Wall**         |                         |                            |
| Density (kg/m³)         |                         | 0.92                       |
| Wall Thickness (m)      |                         | 0.5                        |
| Poisson’s Ratio         |                         | 0.49                       |

Conventionally to model a artery the entire volume inside (blood) and outside (artery wall) would be discretised in to solid elements. The pressure volume relation and the total volume would be the contribution of the addition of all the elements in the entire system. But an artery is not a simple geometry to model; it has many twists and turns. As a result, such geometries experience the limitation of the FEM mesh which is not suitable for such sharp curves and irregular surfaces. As a result, the computation cost would hike up due to these solid elements. Hence there was a need for an alternative approach to replace volume mesh modeling to surface mesh. This could be achieved by modeling the artery as a control volume. In other way it can be interpreted as the entire volume of the artery would be covered by an envelope, which is also termed as the domain. The domain is modeled and meshed by using shell element or membrane mesh. A specific thickness would be assigned to it along with appropriate material for the domain. As there is an existing method in which the surface area, orientation and the
position of the membrane or shell element can be computed and stored at every time step. This property of the control shell element is utilized to calculate the volume of the artery. This control surface area can be related to the control volume of the artery by using the Green’s Theorem. The first two integrals are the integrals over the control volume \( (dv = dx dy dz) \) and the last integral would be the integration of the surface enclosing the control volume, \( n_x \) is the direction cosine between the surface normal and the ‘x’ direction corresponding to the x-partial derivative.

\[
\iiint \phi \frac{\partial \phi}{\partial x} \, dx \, dy \, dz = -\iiint \psi \frac{\partial \phi}{\partial x} \, dx \, dy \, dz + \oint \phi \psi n_x \, d\Gamma 
\]  
(1)

The volume integral can be written as,

\[
V = \iiint dx \, dy \, dz 
\]  
(2)

Comparing the equation (1) and (2) a volume integral can be obtained. Assuming an arbitrary function ‘\( \phi = 1 \)’ and ‘\( \psi = x_x \)’

\[
V = \iiint dx \, dy \, dz = \oint x \, n_x \, d\Gamma 
\]  
(3)

To obtain the volume of the entire control volume the surface integral so obtained from equation (3) can be further added for all the elements of the artery.

\[
\oint x \, n_x \, d\Gamma \cong \sum_{i=1}^{N} \bar{x}_i n_{ix} A_i 
\]  
(4)

Where the \( x_i \) is the average x coordinate \( n_{ix} \) is the direction cosine between the surface normal and the x direction and \( A_i \) is the surface area of the element.

The force equation for the DEM element can be written as,

\[
\hat{f}^{i+1} = \hat{f}^i + \Delta \hat{f}
\]  
(5)

whereas the subscript \( i+1 \) indicates the time increment and the superpose caret (\( \hat{\cdot} \)) indicates the force in the local coordinate system which is along the axis of the element.

Considering the case in which the orientation vector is not used, the global component of the forces for the discrete element are defined by the use of the direction cosine of the elements,

\[
\begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix} = \hat{\mathbf{f}} \begin{bmatrix}
\Delta l_x \\
\Delta l_y \\
\Delta l_z
\end{bmatrix} = \hat{\mathbf{f}} \begin{bmatrix}
n_x \\
n_y \\
n_z
\end{bmatrix} = \hat{\mathbf{f}} \mathbf{n}
\]  
(6)

Where, \( \mathbf{l} \) is the length

\[
\Delta \mathbf{l} = \begin{bmatrix}
\Delta l_x \\
\Delta l_y \\
\Delta l_z
\end{bmatrix} = \begin{bmatrix}
x_2 - x_1 \\
y_2 - y_1 \\
z_2 - z_1
\end{bmatrix}
\]  
(7)
\[ l = \sqrt{\Delta l_x^2 + \Delta l_y^2 + \Delta l_z^2} \]  
\[ \text{(8)} \]

The \((x_i, y_i, z_i)\) are the global coordinates for the nodes of the spring elements. The force obtained in equation (6) would be added and subtracted from first and second node respectively. If the node is attached to the ground the approach used will be same but instead of \((x_2, y_2, z_2)\) the initial coordinates of the node 1 would be used as \((x_0, y_0, z_0)\).

\[
\begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix} = \hat{f} \begin{bmatrix}
x_0 - x_1 \\
y_0 - y_1 \\
z_0 - z_1
\end{bmatrix} = \hat{f} \begin{bmatrix}
x \\\ny \\
z
\end{bmatrix}
\]
\[ \text{(9)} \]

The force-displacement relation would be used in order to determine the increase of element force. There are nine type of force-displacement/velocity relation, among which our study will be concerned with the ‘linear elastic’ force-displacement/velocity relationship. The relation is given by,

\[ \hat{f} = K \Delta l \]  
\[ \text{(10)} \]

whereas the ‘\(K\)’ is the element stiffness and the’ \(\Delta l\)’ is the change in length of the element. The force-velocity relation can be defined for the linear viscous element which is given by,

\[ \hat{f} = C \frac{\Delta l}{\Delta t} \]  
\[ \text{(11)} \]

where ‘\(C\)’ is the viscous damping parameter and ‘\(\Delta t\)’ is the time step increase. In order to consider the strain rate effect, the forces are scaled which are based on relative velocities of all the springs. The static force computed from all the springs are amplified by multiplying a factor which results to obtain the dynamic force.

\[ F_{\text{dynamic}} = \left( 1 + k_0 \frac{V}{V_0} \right) F_{\text{static}} \]  
\[ \text{(12)} \]

\(k_0\) is the user defined input value, \(V\) is the absolute relative velocity and \(V_0\) is the dynamic test velocity.

The deformation limit of the tension- compression of the body is set according to the application. Once the limit of compression-tension is reached the computation of momentum conservation is done and the common acceleration is computed.

\[ \hat{a}_{\text{Common}} = \frac{\hat{f}_1 + \hat{f}_2}{m_1 + m_2} \]  
\[ \text{(13)} \]

Table 2 Stages of DEM
The various stages of the DEM are summarized in Table 2. This approach would be implemented in the study for that the process to setup a simulation goes as follows. A C.T scan of a patient is considered suffering from a ICA aneurysm. This data is then provided to an imaging tool in order to convert the data into a BEM model. The segmentation of the geometry is done prior to converting into a BEM model. The pre-processing of this model is done by importing the model to LS PrePost 4.2 and ANSA V15.0.2. The type of mesh used in this study is the triangular mesh, with a mesh count of 29074 and an aspect ratio of 4.5. After the meshing process is complete it is then imported to LS DYNA R8 which is used as a solver.

The output file is then imported to LS PrePost for further processing. In these various parameters were extracted from the output file such as Von Mises Stress, Average Displacement and Pressure Distribution.

| STAGES | ACTIVITIES |
|--------|------------|
| 1      | Particle Initialization |
| 2      | Collision Detection |
| 3      | Contact Force Calculation |
| 4      | Computing Acceleration Vector |
| 5      | Compute Velocity and Position of All Bodies |
| 6      | Output Data |
The Fluid Solid Interaction model is a type of analysis in which the computational fluid dynamics and the structural analysis are coupled and the results are linked with each other in order to obtain appropriate results. In this study the FEM model is imported to the ANSYS WORKBENCH 14.5. The Artery model is used for the Transient Structural Analysis shown in Figure 3 and the Blood model is used for Computational Fluid Analysis shown in Figure 4.

Both the bodies are meshed in ANSYS 14.5 and type of mesh used was tetra mesh. Mesh count of the Artery and the Blood body obtained was 322332 and 557778 respectively. The boundary conditions used in this analysis is shown in Table 3.
Table 3 Boundary Conditions for FSI Model

| Artery         | Blood          |
|----------------|----------------|
| One inlet and Three outlets | Inlet         |
| Fixed Support  | Velocity Inlet (Pulsating Flow) |
|                | Outlet 1       |
|                | Pressure Outlet|
|                | Outlet 2       |
|                | Pressure Outlet|
|                | Outlet 3       |
|                | Pressure Outlet|

The data file so obtained from the analysis of the secular aneurysm is then imported to CFD POST 14.5 and further processed. Since the main objective of this study was to validate the FEA/DEM based analysis and also to find the WSS. Hence two parameters were extracted during the post processing Wall Shear Stress (WSS) and Von Mises Stress. As it can be see the WSS and Von Mises Stress were obtained from a FSI study for validation of the FEM/BEM method studied earlier, a comparison will help to conclude the similarity of both the methods. This will aid to conclude as the FEM/BEM method can be a parallel approach of studying the aneurysm-based studies.

The aneurysm is of non-uniform thickness hence it is very essential to determine the thickness distribution of the artery wall. This is essential to analyze various phenomenon of the artery using CAE approach. Till date there were many efforts done to find the approximate thickness distribution. Efforts were made by inserting a dye inside the blood stream and the intensity of the MRI would say the area of minimum and maximum thickness though less accurate. Till date the thickness of the artery wall for the modeling of the artery wall in FEA
analysis is considered to be of uniform thickness. This is an assumption made results in inaccurate results.

Considering the similarities in the inflation of the aneurysm and the inflation of the balloon one can obtain the relation of the James-Guth Stress Strain Relation which was introduced by him to find the nature of inflation of the ideal rubber balloon inflation. According to this relation the thickness and the pressure gradient parameters are related for the thickness variation. Also the profile of inflation can be determined from the relation derived from this relation by providing appropriate boundary conditions. Consider a non-uniform inflated domain given in Figure 5.

![Figure 5 Non-uniformly Inflated Domain](image)

Now consider a point ‘p’ in the center of the domain which is fixed and is equidistant from all the nodes of the domain and the inflation of the domain is in the direction of the unit normal ‘n’. Consider the pressure outside the domain to be atmospheric $P_{\text{out}}$ and the inside pressure to be $P_{\text{in}}$. As this condition will be considered to be the initial condition after a particulate period of time ‘t’ seconds the inflation of the domain occurs and the point ‘Q₀’ further displaced to ‘Q’. The distance between the two points increases from $r₀$ to ‘r’.

- Application of James-Guth Stress Strain Relation for an Ideal Rubber.

$$f_i = \frac{1}{L_1[kKT\left(\frac{L_1}{r_0}\right)^2-pV]} \quad \text{(James-Guth Stress Strain Relation)}$$  \hspace{1cm} (14)

In this algorithm the pressure gradient at various stages are considered. The gradient is considered between the interior of the aneurysm and its exterior. This equation if then derived further to obtain

$$P_{\text{in}} - P_{\text{out}} = \frac{f_t}{\pi r^2} = \frac{C}{r^2[1-(\frac{r_0}{r})^6]}$$  \hspace{1cm} (12)
Using the boundary conditions the constant ‘C’ can be obtained. From this equation we can further derive the relation between thickness and distance of the aneurysm from the fixed center.

\[
\frac{t}{t_o} = \left(\frac{r_o}{r}ight)^2
\]  
(13)
(Relation between thickness and radial distance of a node from a common point)

Now to prove the above explained method a case study will be considered in which the theoretical and the simulation results will be compared. The comparison is shown in Table 4.

3. Results & Discussions

The case study done to validate the James-Guth stress strain relation by results obtained in both simulation and the theory calculations are very close. This algorithm can be put in to a computer programming code and thus predicting thickness would be easy. The database of the pressure gradients at various stages can be prepared and the database can be linked to the work which would possess the logic as the relation of thickness and distance between the two points of consideration, in the CAE study it would be the nodes which would be considered. This method can be further studied as a research field for better understanding.

| CASE STUDY | Initial Pressure (2.409E-06 Pa) | Final Pressure (0.2409E-06 Pa) |
|-----------|---------------------------------|-----------------------------|
| Pressure  |                                 |                             |
| Shell Thickness (m)   | 0.0415 (simulation value)        | 0.0376                       |
| Linear Extension Of a Node From a Fixed Centre Point Of Saccular Aneurysm (m) | 14.6939 (simulation value) | 15.1708 |

Till date rupture mechanics of an aneurysm was conducted using the FSI method. The analysis took 900 minutes to complete where as the FEM/DEM simulation using took 126 minutes to converge. If WSS is to be obtained, then an internal flow CFD analysis with a pulsating flow was done with a computation time of 310 minutes. Thus both analyses together tool 436 minutes. Thus there is a percentage computation time reduction of 51.55 %. The
curiosity of an individual would be ignited to find the reason of such a drastic reduction of computation time. The answer to that would be, CFD study requires volume mesh whereas FEM/DEM uses surface mesh. If an FSI approach is to be considered, in addition to the artery wall volume mesh there is a volume mesh of the flowing fluid. But if the FME/DEM approach is considered the artery wall would be shell meshed and there is no need to provide a volume mesh for the flowing fluid. The use of DEM in LS-DYNA eliminated the use of volume mesh. Thus the number of elements is reduced. As number of element is directly proportional to the computational time, the time reduction is achieved. Figure 6 shows the meshed model of an ICA saccular aneurysm.

Figure 6 Shell Mesh Model

As we have seen that based on an observational study done by Jonathan Russin et al (2015) of the blood flow pattern doctors can predict the effectiveness of the treatment at every intervention. Thus appropriate measures can be taken in order to decide the further method of treatment.

The WSS value obtained from the CFD analysis was 3.5 Pa. According to the study done by Masaaki Shojima et al (2007) this value is considered to be in the safe range according to the previous study. Figure 7 shows the WSS contour.
Aspect ratio obtained from the geometric specifications of the aneurysm was found to be 1.5. This aspect ratio is considered to be safe and the odds of rupture phenomenon to occur are very less. The ground on which the statement proves to be true is the previous studies done on similar topic. According to Weir B eta al (2003) the aneurysm up to AR of 1.8 is likely to be unruptured but as the aneurysm AR reaches 3.4 the chances of it getting rupture is maximum.

The Inflow Angle has a greater significance to the cause of rupture it also influences the WSS. It was observed that as the IA increases the peak velocity and the shear jet zone of the aneurysm increases. The shear jet zone is the zone near the neck of the aneurysm where maximum shear action occurs due to the blood flow at high pressure. In our case the IA was found to be 85°, according to Merih Ieta al (2010) the influence of IA would be moderate as the angle lies between 60° to 140°. This range of IA was studies in a previous study and hence taking under consideration this study we can say the aneurysm rupture chances are less due to IA of 85°. Figure 8 provides the displacement contour which is having the influence of the IA as the maximum displacement was found to be at the tip of the aneurysm. As greater the IA angle the horizontal component of fluid force increases causing greater displacement to compensate for the increase in the kinetic energy of the fluid.

In the past there were many efforts done by Shang EK eta al (2013) to study the significance of the variable thickness of the aneurysm body. Due to this there is a non-homogeneous inflation in an aneurysm in most of the cases. Till date in order to simulate the rupture mechanism of an aneurysm the thickness of the wall is assumed to be uniform. Even though the simulations are
very precise, there will always be an error factor that would be the huddle for any study to obtain the precise results.

![Figure 8 Max displacement 2.46e-05 m](image)

But using the James-Guth’s Stress Strain relation for the ideal rubber not only helps to predict the variable thickness distribution at any point on the aneurysm but also aids us to predict the appropriate inflation profile of the aneurysm at every stages of inflation with respect to the pressure gradient between inside and outside of the aneurysm. This can be achieved by putting the equation as an algorithm in any programming language and the series of pressure gradient data would be acquired from the simulation itself. This method can be considered as one of the significant scope of this study. Figure 9 shows the pressure distribution contour inside the aneurysm.

![Figure 9 Max Pressure is 7.583e-09 Pa](image)
Maximum pressure obtained was $7.583 \times 10^{-9}$ Pa. Taking into consideration the mesh parameters of the BEM study and the CFD study the validation process was successfully achieved as the Von Mises Stress obtained from FEM/DEM and CFD analysis was found to be 0.32 Pa and 0.4 Pa, respectively. Since the difference was of 0.08 Pa the result was satisfactory. Figure 10 shows the contour of Von Mises Stress obtained from the CFD study

![Figure 10 Simulation Results of FEM and DEM: Von Mises Stress 0.318 Pa](image)

The simulation so obtained by the FEM/DEM simulation is very helpful for the prediction of aneurysm rupture and also to study the flow pattern. This can be seen in the simulation result shown in Figure 10

4. Conclusion

The process of FEM/DEM analysis was comparatively simpler than the CFD process. The Von Mises Stress obtained from both the study after comparison was found to have the difference of 0.08 Pa.

But due to the reduction in the computation time for the objective to achieve by both the approach had a significant variation. The use of FME/DEM approach along with the regulars CFD approach instead of the conventional CFD study using the FSI model would reduce the computational time by 51.55%.

Thus the advantage of less computation time by using BME process for the rupture mechanism study outwits the minor difference of the Von Mises stress. Also using the Corpuscular method, a person can even study the flow pattern of the blood, this further adds to the advantages of the FEM/DEM study.

Based on the case study done to validate the use of James-Guth’s Stress Strain relation for ideal rubber the values of thickness and the distance of a node from a common center distance
was found to be 10.37% and 3.16%. Assuming the error in the CAE analysis to be +10%. The results acquired are satisfactory and precise. Hence use of the James-Guth’s equation will enhance the future studies related to aneurysm.

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