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HEMODYNAMIC EXAMINATION AND INTERPRETATION OF RUPTURE IDENTIFICATION IN INTRACRANIAL ANEURYSM BASED ON COMPUTATIONAL FLUID DYNAMICS SIMULATIONS

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Abstract: Owing to its clinical importance, there has been a growing body of research on understanding the hemodynamics of cerebral aneurysms. Determination of particular aneurysm (diagnosed by Computed Tomography, Magnetic Resonance Imaging) has a high risk of rupture so that it can be treated before bleeding occurs on the intracranial wherein the neurosurgeons fail to judge the risk of rupture even with their profound experience. Traditionally, it has been performed using general- purpose, state-of-the-art commercial solvers. Rupture prediction has meant requiring engineering expertise for making appropriate choices on the geometric discretization, time-step selection, choice of boundary conditions etc. Hemodynamic analysis of cerebral aneurysms has been widely carried out to clarify the mechanisms of their growth and rupture. Computational fluid dynamics technology used to estimate the nature of blood flow with parameters including pressure distribution, wall shear stress and boundary conditions to identify the rupture site and examine the hemodynamic calculation. Based on patient condition the accurate and reliable treatment can be given by estimating hemodynamic analysis of aneurysm using Computational Fluid Dynamics technology.

Keywords: Cerebral aneurysm, Hemodynamic analysis, Computational fluid dynamics, Wall shear stress.

INTRODUCTION

We focused on to predicting the rupture of brain aneurysm. The worst cause of death is heart vessel disease and second one is cerebrovascular disease. The typical symptoms of vascular disease are vascular occlusion and aneurysm. A brain aneurysm is called as cerebral or Intracranial Aneurysms. It is an abnormal bulging outward of one of the arteries in the brain. Brain aneurysms are often discovered when they rupture, causing bleeding into the brain or the space closely surrounding the brain called the subarachnoid space causing a Subarachnoid Hemorrhage (SAH). SAH from a ruptured cerebral aneurysm can lead to hemorrhagic stroke, brain damage and death. Hence, it is required to determine whether the particular aneurysm has a high risk of rupture so that it can be treated before bleeding occurs. There are certain cases wherein neurosurgeons fail to judge the risk of rupture even with their profound experience and decide not to meddle with it. Such was a problem that was shared with us by a group of doctors wherein we are supposed to predict the rupture status of Intracranial Aneurysm. Rupture of intracranial saccular aneurysms is the most common cause of spontaneous subarachnoid hemorrhage, which has significant morbidity and mortality.

Although there is still controversy regarding the decision on which unruptured aneurysms should be treated, this is based primarily on their size. Nonetheless, many large lesions do not rupture whereas some small ones do. It is commonly accepted that hemodynamic factors are important to better understand the natural history of cerebral aneurysms. However, it might not always be practical to carry out a detailed computational analysis of such factors if a prompt assessment is required. Since shape is likely to be dependent on the balance between hemodynamic forces and the aneurysm surrounding environment, an appropriate morphological 3-D characterization is likely to provide a practical surrogate to quickly evaluate the risk of rupture. Reliable early prediction of aneurysm rupture can greatly help neurosurgeons to treat aneurysms at the right time, thus saving lives as well as providing significant cost reduction. Most of the research efforts in this respect involve statistical analysis of collected data or simulation of hemodynamic factors to predict the risk of aneurysm rupture.

An efficient and novel methodology for 3-D shape characterization of earlier cerebral aneurysms rupture is described. By calculating the hemodynamic factors of brain aneurysm it can predict the rupture status. Cerebral aneurysms are weak or thin spots on blood vessels in the brain that balloon out. While the majority of aneurysms do not burst, those that do would lead to serious complications including hemorrhagic stroke, permanent nerve damage, or death. Yet, surgical options for treating cerebral aneurysms carry high risk to the patient. It is vital for the doctors to accurately diagnose aneurysms that have high probabilities of rupturing.

Application, the patient dataset has many attributes, ranging from patient profile to results from diagnostic test and features extracted from brain images (CTA/MRA).These CT/MRI angiogram images are taken to processing the aneurysm region and to find the ruptured region in the aneurysm based on CFD Simulations. Image segmentation, Discretization FEA model, Solving CFD, Post processing methods are applied and calculating the hemodynamic parameters such as velocity, shear stress, pressure distributions of aneurysm, from these parameters the post processing and preprocessing of aneurysm rupture can be predicted.

CLINICAL STATEMENT

An estimated 6 million people in the United States have ruptured brain aneurysm, or 1 in 50 people. The annual rate of rupture is approximately 8 – 10 per 100,000 people or about 30,000 people in the United States suffer a brain aneurysm rupture. There is a brain aneurysm rupturing every 18 minutes. Ruptured brain aneurysms are fatal in about 40% of cases. of those who survive, about 66% suffer some permanent neurological deficit. Approximately 15% of patients with aneurysm subarachnoid hemorrhage (SAH) die before reaching the hospital. Most of the deaths from subarachnoid hemorrhage are due to rapid and massive brain injury from the initial bleeding which is not correctable by medical and surgical interventions. 4 out of 7 people who recover from a ruptured brain aneurysm will have disabilities. Brain aneurysms are most prevalent in people ages 35 – 60, but can occur in children as well. The median age when aneurysm hemorrhagic stroke occurs is 50 years old and there are typically no warning signs. Most aneurysms develop after the age of 40 and are small, about 1/8 inch to nearly one inch, and an estimated 50 to 80 percent of all aneurysms do not rupture during the course of a person's lifetime. Aneurysms larger than one inch are referred to as "giant" aneurysms and can pose a particularly high risk and can be difficult to treat.

Women, more than men, suffer from brain aneurysms at a ratio of 3:2. African-Americans at twice the rate of rupture of whites (a 2.1:1 ratio) Hispanics at nearly twice the rate of rupture of whites (a 1.67:1 ratio) Ruptured brain aneurysms account for 3 – 5% of all new strokes. Subarachnoid hemorrhage (SAH) is one of the most feared causes of acute headache upon presentation to the emergency department. Headache accounts for 1 – 2% of the emergency room visits and up to 4% of visits to the primary care offices. Among all the patients who present to the emergency room with headaches, approximately 1% has subarachnoid hemorrhage. One study put the figure at 4%. Accurate early diagnosis is critical, as the initial hemorrhage may be fatal, may result in devastating neurologic outcomes, or may produce minor symptoms. Despite widespread neuro- imaging availability, misdiagnosis or delays in diagnosis occurs in up to 25% of patients with subarachnoid hemorrhage (SAH) when initially presenting for medical treatment. Failure to do a scan results in 73% of these misdiagnoses. This makes SAH a low-frequency, high-risk disease. There are almost 500,000 deaths worldwide each year caused by brain aneurysms and half the victims are younger than 50. Based on a 2014 study, the combined lost wages of survivors of brain aneurysm rupture and their caretaker for a year were $138,000,000.The cost for brain aneurysm treatment by clipping via open brain surgery more than doubles in cost after the aneurysm has ruptured. The cost of a brain aneurysm treated by coiling, which is less invasive and is done through a catheter, increases by about 70% after the aneurysm has ruptured. 10 – 15% of patients diagnosed with a brain aneurysm will harbor more than one aneurysm. The federal government only spends approximately $0.83 per year on brain aneurysm research for each person afflicted. The treatment for brain aneurysm is difficult procedure rather than other type of disorder.

Aneurysms are two types ruptured and unruptured aneurysm, the unruptured aneurysm doesn't have high risk but the ruptured aneurysm cause high risk which causes the stroke leads to sudden death.
The Computational Dynamic Fluid provides reliable treatment by simulation of aneurysm angiogram images. The preprocessing and post processing of aneurysm can be done this method.

METHODOLOGY

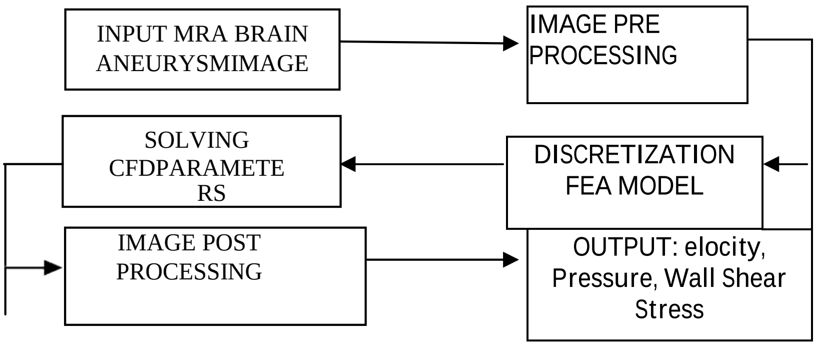

Figure: Block diagram

IMAGE PRE-PROCESSING

Image Processing is a technique to enhance raw medical images received from CT, MRI, and Fluoroscopy for various applications. This field of image processing significantly improved in recent times and extended to solving the hemodynamic parameters by Computational Fluid Dynamics. The image processing mainly deals with image acquisition, Image enhancement, image segmentation, feature extraction, image classification etc. The basic definition of image processing refers to processing of digital image, i.e. removing the noise and any kind of irregularities present in an image using the digital computer. The noise or irregularity may creep into the image either during its formation or during transformation etc. For mathematical analysis, an image may be defined as a two dimensional function f(x, y) where x and y are spatial (plane) coordinates, and the amplitude of f at any pair of coordinates (x, y) is called the intensity or gray level of the image at that point. When x, y, and the intensity values of fare all finite, discrete quantities, we call the image a digital image. It is very important that a digital image is composed of a finite number of elements, each of which has a particular location and value. These elements are called picture elements, image elements, and pixels. In image preprocessing, image data recorded by CT/MRI restrain errors related to geometry and brightness values of the pixels. These errors are corrected using appropriate mathematical models which are either definite or statistical models. Image enhancement is the modification of image by changing the pixel brightness values to improve its visual impact. Image enhancement involves a collection of techniques that are used to improve the visual appearance of an image, or to convert the image to a form which is better suited for human or machine interpretation. In image enhancement, the goal is to accentuate certain image features for subsequent analysis or for image display. Examples include contrast and edge enhancement, noise filtering, sharpening, and magnifying. Image enhancement is useful in feature extraction, image analysis and an image display. The enhancement process itself does not increase the inherent information content in the data. It simply emphasizes certain specified image characteristics. Enhancement algorithms are generally interactive and application dependent.

Pre-processing in the CFD workflow involves the preparation of geometry, meshing the geometry, setting up the material properties, initial and boundary conditions. Having a good geometry of CT/MRI image is one without defects is crucial for the setup of a CFD analysis. Common geometry defects are: Missing face, Missing face geometry example, Example of missing face, Overlapping faces, Gaps, Free faces, edges, nodes, Sharp angles, Preparing the Geometry, Fill the gaps, Split surfaces with high curvature, Remove unnecessary details. At the end of the preparation stage, the geometry should be a clean, watertight solid. It can be uploaded in different formats such as .stp/.step, .stl, .iges or .brep, but the recommended one is .stp/.step because it is more stable than other formats.

IMAGE DISCRETIZATION

Discretization refers to the process of translating the material domain of an object-based model into an analytical model suitable for analysis. In structural analysis, discretization may involve either of two basic analytical-model types, Finite-element model, in which a meshing procedure creates a network of line elements connected by nodes within a material continuum. Each line element simulates the geometric and physical properties of the local material.

Given the loading and boundary conditions of the whole system, numerical formulation of structural response may advance through the computational model. The discretization of a finite-element model will have some degree of refinement, producing either a coarse or fine mesh. A node-element model is technically a finite-element model in which a single line element represents the structural element.
Node-element modeling, however, follows the direct stiffness method, whereas finite-element modeling follows the Finite-Element Method (FEM). Mesh generation is a crucial step in the CFD workflow. It divides the physical domain into a finite number of discrete regions called control volumes or cells. The numerical solution is calculated in these individual cells by solving the governing fluid flow equations inside. How the mesh should be refined depends on the specific problem. For example, care must be taken to ensure that areas with large changes in fluid properties are adequately refined. In this respect, the physics of the problem helps. Make an intuitive guess of the flow profile and then refine the areas of the large gradients. Always start with a coarse mesh and then gradually refine the mesh for the specific areas. Keep the mesh size as small as possible within accuracy limits. Discretization of Finite Element Method involves with Partial Differential Equations (PDEs) are widely used to describe and model physical phenomena in different engineering fields and so also in microelectronics fabrication. The most universal numerical method is based on finite elements.

The most universal numerical method is based on finite elements. This method has a general mathematical fundament and clear structure. Thereby, it can be relative easily applied for all kinds of PDE s with various boundary conditions in nearly the same way. The finite element method (FEM) has its origin in the mechanics and so it is probably the best method for calculating the displacements during oxidation processes. The finite element formulation works on a large number of discretization elements and also on different kinds of meshes within the domain. Furthermore, it also provides good results for a coarse mesh. It can easily handle complicated geometries, variable material characteristics, and different accuracy demands.

SOLVING CFD

The simulation model is selected based on the physics of the problem. The first step is to select the simulation type (incompressible, compressible, natural convection, etc.). Once the simulation type is selected, set the other physical problem parameters. For example, if you want to calculate the effects of turbulence on the fluid flow, set turbulence as a parameter, or, in contrast, set it to laminar if you want to neglect the effects of turbulence on the fluid flow. If the fluid flow is time-dependent, you can choose the transient setting and if you need a solution which is independent of time, selecting the steady state option would be best. This solver is defining the work flow with the Specification of Initial and Boundary Conditions. Now we have to provide the material properties, initial conditions, and boundary conditions. Assign the material properties to the fluid. One of the most important parts of setting up a numerical simulation is giving the initial and boundary conditions. Numerical simulations are based on solving the partial differential equations on the given domain, and these equations require the initial and boundary conditions depending on the problem type to be well posed. This describes the basic workflow for running a CFD simulation. It Solve quick edit dialog provides tools to define the physical model, specify how often results are saved, and to run the simulation.

It uses the Physics tab to enable physical models such as flow and heat transfer, the Control tab to specify analysis parameters such as steady state or transient and to set the number of iterations and the Adaptation tab to progressively improve the mesh by running the simulation multiple times. At the end of each run, Adaptation modifies the mesh based on the results, and uses the new mesh for the next cycle. The result is a mesh that is optimized for the particular simulation. The mesh is finer for high gradient regions and coarser elsewhere.

POST PROCESSING

The next step of post processing is specifying the numerical parameters, i.e. setting up solver parameters, discretization schemes, etc. Depending on the simulation type, every problem has its own unique structure. Usually, one problem can be solved by multiples solvers and with different solver parameters; however, to efficiently solve the problem, it is very important to give the correct solver parameters and numerical schemes. One of the major parts of any numerical simulation is interpreting the results. This is done in post-processing. The flow fields are analyzed by different filters like streamlines, contour plots, etc. Post-processing is the final step in the CFD workflow, and it allows you to visualize your simulation results and make decisions for design optimization.

Algorithm

Algorithm followed in Computational Fluid Dynamics is Finite Element Method (FEM). The Finite Element Method (FEM) is a numerical method for solving problems of engineering and mathematical physics. It is also referred to as Finite Element Analysis (FEA). Typical problem areas of interest include structural analysis, heat transfer, fluidflow, mass transport, and electromagnetic potential. The analytical solution of these problems generally requires the solution to boundary value problems for partial differential equations.

The finite element method formulation of the problem results in a system of algebraic equations. The method yields approximate values of the unknowns at discrete number of points over the domain. To solve the problem, it subdivides a large problem into smaller, simpler parts that are called finite elements.The simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem. FEM then uses variation methods from the calculus of variations to approximate a solution by minimizing an associated error function.

Principles of Finite Element Method

The basic idea of FEM is to discretize the domain of interest, where the PDE is defined, in order to obtain an approximate solution of the PDE by a linear combination of basic functions defined within each sub domain. Then, the assembly of sub domains, which is based on the process of putting the finite elements back into their original positions, results in a discrete set of equations which are analogous to the original mathematical problem. The entire domain under investigation is approximated as an assembly of discrete elements, so- called finite elements, interconnected at points common to two or more elements, so-called nodes. Each finite element is an independent geometric region of the domain over which equations with unknown variables of the given problem are defined using the governing equations of the Mathematical model of interest. In each finite element, these equations are solved by assuming basis functions which interpolate the unknown variables over the finite element, in order to approximate the solution of the problem within the element. The basis function is defined within the finite element using the values of the unknown variables at the nodes. The approximate solution to the problem within the element is obtained as a linear combination of nodal values of the variables and the basic functions for the element. The equations for the finite element relate the nodal values of the variables to other parameters. The formulation of the finite element analog of a model equation follows two main approaches, namely weighted- residual and weak formulation. Then, with appropriate loadings, boundary, and initial conditions applied to the elements/nodes, the local element equations for all the finite elements are assembled together and solved simultaneously to obtain a continuous solution in terms of its values at the nodes.

The finite element method (FEM) is used in structural analysis of solids, but is also applicable to fluids. However, the FEM formulation requires special care to ensure a conservative solution. The FEM formulation has been adapted for use with fluid dynamics governing equations Although FEM must be carefully formulated to be conservative; it is much more stable than the finite volume approach.

RESULTS AND DISCUSSION

The aim of this exercise is to load in a predefined software workflow and perform all the steps from loading the DICOM image (acquired using XA modality) of an intracranial aneurism with the surrounding vessels to the comparison of the aneurysm shape with another aneurysm. The exercise shows how to crop the image to isolate the region of interest (containing the aneurysm), extract the aneurysm geometry, and perform different mesh editing operations to edit and refine the aneurysm geometry, and activate different visualization options, e.g. volume rendering of the vessels, visual representations of the geometry, multiple windows for shape comparison, etc.

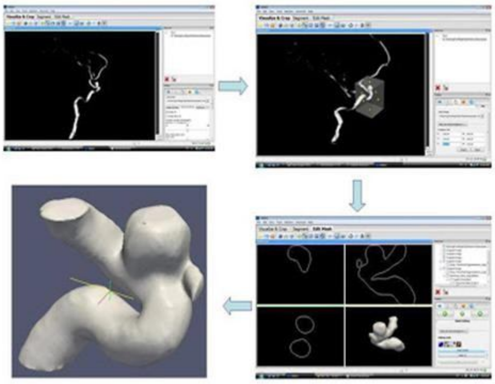

Figure: 3D angiogram image segmented

This problem usually arises in large vessels that are exposed to backflow in 3D and 2D flow simulations. This phenomenon may be a cause of divergence of the numerical scheme due to bulk reversal of the flow through an outlet, localized areas of flow reversal or use of a boundary 0D circulation model. Accurate simulation of blood flow in vessels requires the repeated solution of linear systems of equations with millions of unknowns. Moreover, use of closed-loop boundary models significantly increases the degree of coupling between boundary degrees of freedoms. The **svLS** linear solver is designed to efficiently handle large cardiovascular simulations with arbitrary boundary conditions and reduce solution times.

Coupling a three-dimensional finite element solver with a 0D lumped circulation model drastically improves the possibility of realistically simulate patient-specific hemodynamics and physiology. This solver setting initial conditions and boundary conditions of aneurysm, setting mechanical properties for vessel walls (if deformable), setting parameters for Flow solver, running the flow solver, converting and analyzing the simulation results of the aneurysm model. We will do this considering very simple geometry (a straight cylinder) to illustrate different points in a simple way to model the simulation of aneurysm.

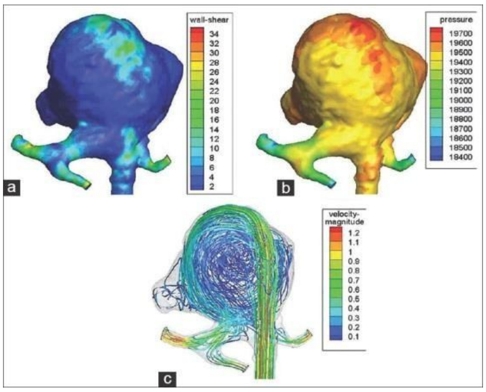

Figure: Aneurysm applied on contour by CFD simulation

CONCLUSION

CFD technology used to examine the hemodynamic parameters of intracranial aneurysm. Hemodynamic analysis is of cerebral aneurysms has been widely carried out to clarify the mechanism of their growth and rupture. The parameters such as pressure distribution, velocity, wall shear stress, are calculated, based on this measurement the mechanism of aneurysm can be identified. Three different methodologies; image preprocessing, image discretization, solving CFD and post processing can be done. Each step, the processing of aneurysm occurs. The post processing analysis of intracranial aneurysm determines whether the aneurysm is going to rupture or not. FEM algorithm used to analyses each and every element of the blood vessel structure. Using CFD the pre and post analysis of aneurysm rupture can be identified.

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