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A Patient-Specific Computational Framework Utilizing CFD and Bio-Numerical Modelling to Predict Growth of Abdominal Aneurysms for Therapeutical Aid

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ABSTRACT

This research aims at devising a framework between a CFD model and a derived biomechanical model that effectively makes AAA (abdominal aortic aneurysms) therapeutics more accurate. The input data required is patient abdominal CT-imaging scans using CAD software and features we can extract out of the vessel geometry in which, after meshing, we can simulate the blood flow using CFD in Ansys Fluent. This blood flow CFD simulation helps us identify the high-pressure or stressed regions of the vessel wall. Using the biomechanical factors affecting aneurysmal expansion, a model to quantify expansion per unit time was derived. This model took into consideration factors like compliance, elastic modulus, and other mechanical properties. Using the geometrical parameters that can be acquired from VMTK processing on the CAD vessel geometry and variable parameters like pressure and velocity from the CFD simulation, the date of rupture can be approximated, thus precisifying aneurysmal therapeutics.

Keywords: *CFD, CAD, Biomechanics, Abdominal Aortic Aneurysms, Ansys Fluent*

INTRODUCTION TO PROBLEM

Abdominal aortic aneurysms (AAA) are local enlargements of the abdominal aorta, occurring below the renal bifurcation. These are a prevalent cardiovascular health disease, affecting 35.12 mil- lion individuals globally and leading to death of around 200,000 patients per year. Causes include tobacco induction, hypertension, and genetic fac- tors. AAA rupture results in rapid hemorrhagic shock and multiple lower body organ failures. The main organs dependent on the blood sup- ply by the abdominal aorta, such as kidneys and parts of the alimentary canal, can fail if the ab- dominal aorta ruptures. Currently, all known treatments for AAA are surgical, including open surgical repair and endo-vascular surgery. In hu- man anatomy, the abdominal aorta is the largest artery in the human body. In the abdominal cavity the aorta branches out, which form an ex- tensive network supplying blood to the stomach, liver, pancreas, spleen, small and large intestines, kidneys, reproductive glands, etc.

FLAWS IN CURRENT THERAPEUTICS (RATIONALE)

After consulting experienced cardiothoracic sur- geons (see Acknowledgments) and asking them about the current course of treatment for AAA, I formulated the following gaps in current therapeutics for AAA: 1) After performing CT, MRI or other imaging tests doctors determine the di- ameter of the abdominal aorta; (i) If the diameter is larger than 5.5 cm, doctors carry out invasive treatment, (ii) If the diameter is smaller than 5.5cm, the doctors perform drug regulation by using ACE inhibitors to regulate blood pressure, and suggest no further tobacco consumption. 3) To predict the date of rupture and rate of expan- sion, doctors use their clinical experience, largely based on the observations of previous patients, which has been proven to be mostly inaccurate.

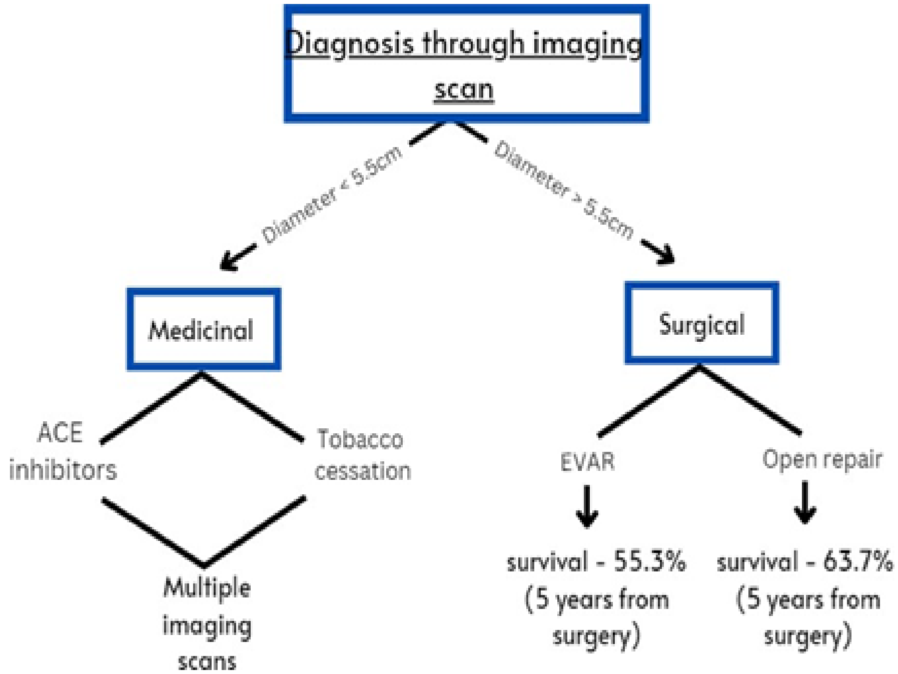


Figure 1: Graphical representation of AAA therapeutics

Surgical intervention for AAA poses a serious threat to the individual's life because EVAR and open repair are extremely com- plicated surgeries with survivability rates of around 55.3% (EVAR) and 63.7% (open re- pair), respectively, so a long-run prediction is required to give doctors an idea of whether to ”intervene or not.”

AAA growth patterns are extremely unpredictable as they can vary hugely in both the cases; 1) sudden increase in expansion rate,

2) sudden decrease in expansion rate, which can sometimes lead to mistreatment of AAA.

There is a high chance that abdominal aorta could rupture before getting up to the diameter of 5.5cm (3% - 15% according to American Association for Vascular Surgery), and doctors rely solely on this benchmark for the surgical treatment which proves to be highly ineffective and a major cause of death from AAA therapeutics.

The solution consists of a computational frame- work that has the potential to reduce the fatalities of AAA therapeutics drastically. Using a real- time digital simulation of blood flow based on the geometry of the patient's abdominal aorta and a mathematical model to predict abdominal aortic ruptures and expansion rate with a validated ac- curacy. This model will enhance the accuracy of the therapeutics to save multiple lives from the procedure by removing human-estimation based practises.

METHODOLOGY/PROCEDURE

The model is mainly divided into two major parts i.e. simulation and mathematical model. The following steps depicts the detailed prototype gen- eration of both the parts. The prototype consists of the goal of rendering the simulation in the Iliac bifurcation, since it is the region with the highest computational complexity in the entire aortic region. No human sample was taken in the process and imaging scans and other statistical data was acquired from online repositories. Fur- ther details regarding the sources can be found in the references page.

3D MODELLING AND RECONSTRUCTION

Aim - To digitally reconstruct a 1-1 replica of the patient's Abdominal Aorta on the basis of geometrical data acquired through a CT scan to create a mesh for the simulation.

Utilizing computed tomography (CT) abdomen scans procured from online repositories such as 3D Embodi and the NHIA database in NRRD file format with saggital, axial and coronal view of abdomen CT. A meticulous 1-1 reconstruction of the abdominal cavity of patients was meticulously orchestrated employing the open-source software known as 3D Slicer—an advanced tool designed for scientific data visualization. The CT scans were seamlessly imported into 3D Slicer, where a distinctive segment dedicated to the abdominal aorta was meticulously delineated within the ”segmentations” module. The following figure depicts the abdominal aortic segments in axial and sagittal CT scans.

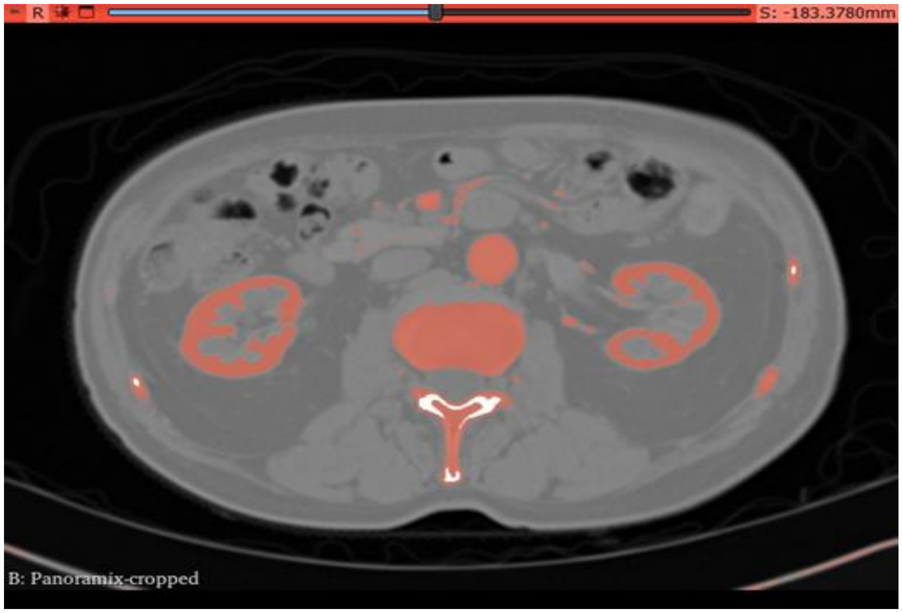


Figure 2: Axial Segmentation

Figure 3: Sagittal Segmentation

An additional extension employing the ”fast marching” algorithm was incorporated. The max- imum pre-initialization volume for fast marching was meticulously set at 1%, while the segmenta- tion volume was judiciously established at 67% to achieve an optimal balance between detail and accuracy in modeling the abdominal aorta. A smoothing kernel size of 5.00mm (or 5x3x3 pix- els) was applied, utilizing a ”Median” smoothing median, to eliminate extrusions while preserv- ing anatomical fidelity. The resultant model of the abdominal aorta was subjected to meticulous rendering. Extraneous particles and glitches orig- inating from the CT scans were systematically expunged through manual intervention, employ- ing the segment crop tool to ensure a pristine representation of the abdominal aorta.

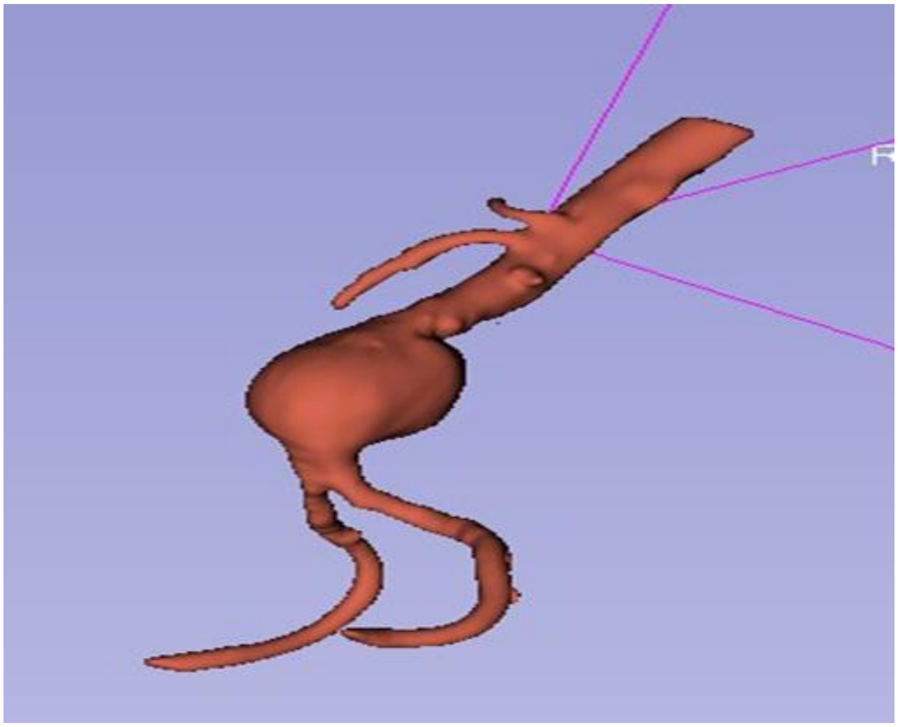


Figure 4: Reconstruction of the abdominal aorta

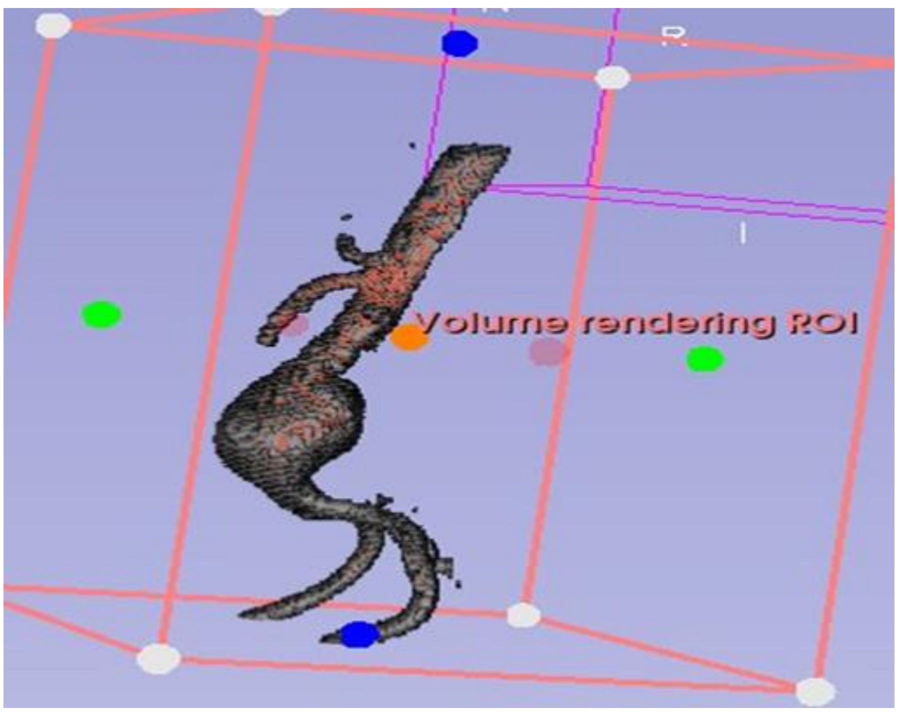


Figure 5: Source volume - panaromix cropped

However, for the purpose of simulation, it was im- perative to transform the non-hollow model into a hollow one. To accomplish this, an additional ex- tension was employed, featuring a ”hollow” tool with a specified shell thickness of 3.00 mm (or 3x3x3 pixels). The existing segment served as the ”inside surface” for this operation, culminating in the successful hollowing of the abdominal aorta and rendering it amenable to simulation processes. Furthermore, the intricate bifurcation of the ab- dominal aorta, specifically the iliac bifurcation, was meticulously isolated. This anatomical fea- ture was characterized by a single inlet and four outlets. Leveraging the Vascular Modelling Tool Kit (VMTK) extension, the geometric dimensions of the iliac bifurcation were extracted to facilitate the subsequent development of the biomechanical model.

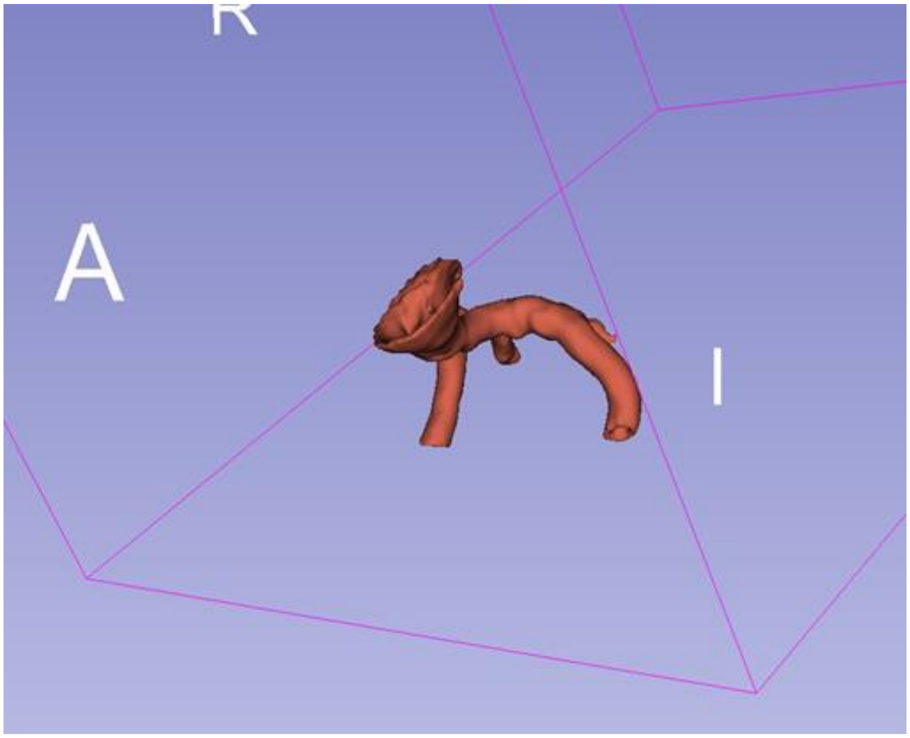


Figure 6: Reconstruction of hollow iliac bifurcation

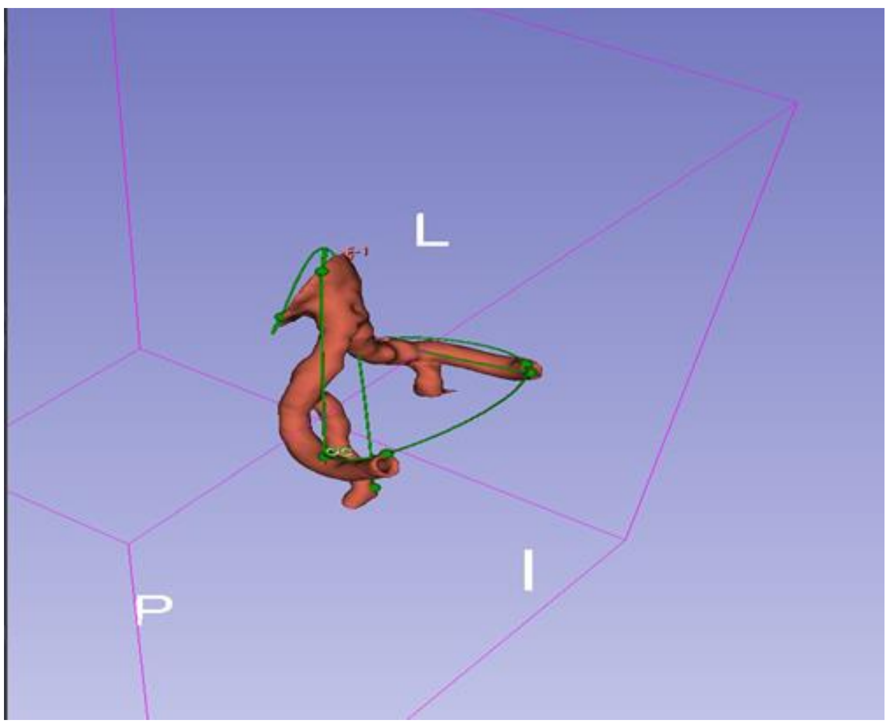


Figure 7: VMTK processing pathway on hollow iliac bifurcation

The meticulously acquired geometry of the iliac bifurcation was ultimately exported in STL file format. This intricate process reflects a sophisticated integration of medical imaging, mathemat- ical algorithms, and specialized software tools within the realm of academic exploration and biomedical engineering.

MESH GENERATION AND SIMULATION

Aim

Mesh generation and simulation solving

Aim - To generate a real-time simulation implying CFD, FEA to give the visual data of the abdominal aorta and display the pressure gradient, velocity streamline and eddy's viscosity of the abdominal aorta.

The geometric data of the iliac bifurca- tion, initially presented in STL (standard triangle language) format, underwent meticulous correction of facet and node alignments using the gmsh software which is finite-element mesh generator. Subsequently, the refined STL geometry was introduced into MeshLab (a 3D mesh processing software system) where comprehensive checking and repair algorithms were executed. In addition, mesh element size and density reduction were imperative, prompting the application of Quadric Edge Collapse Decimation (QECD) twice, initially targeting 10,000 facets and subsequently 5,787 facets, effectively mitigating file complexity. The resultant STL file was then imported into FreeCAD (a general-purpose parametric 3D computer-aided design modeler) wherein the conversion of the STL format into a solid with distinct hollow and outer components was achieved through the deployment of the part tool. The ensuing STEP (ISO 10303) file derived from this process was deemed essential for subsequent simulation endeavors.

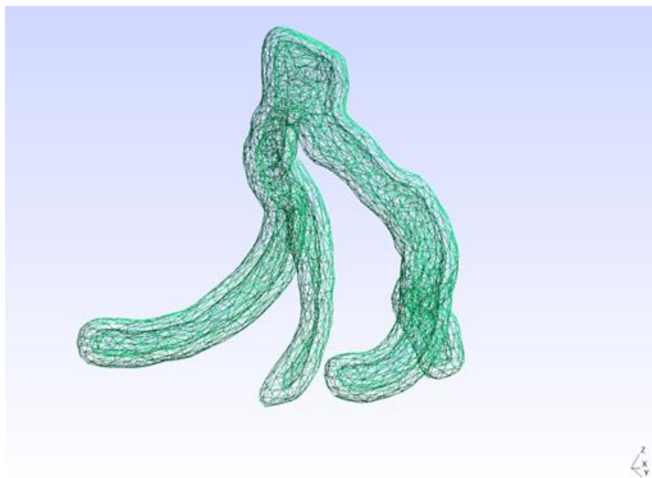


Figure 8: Geometry correction results of gmsh

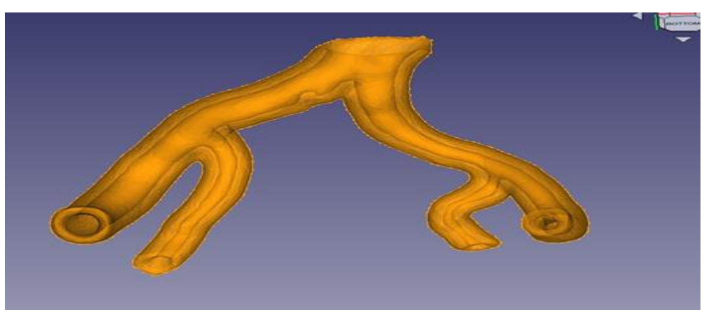


Figure 9: The result of STEP conversion from FreeCAD

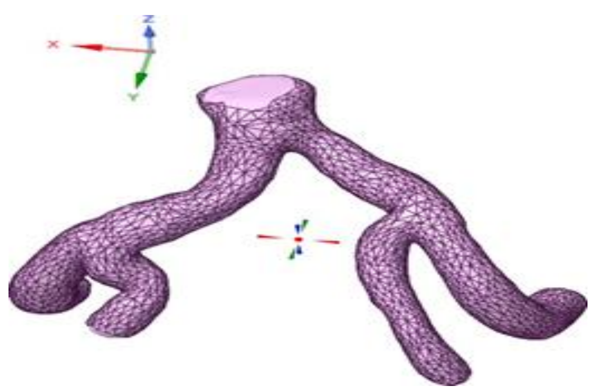


Figure 10: Before facet merging

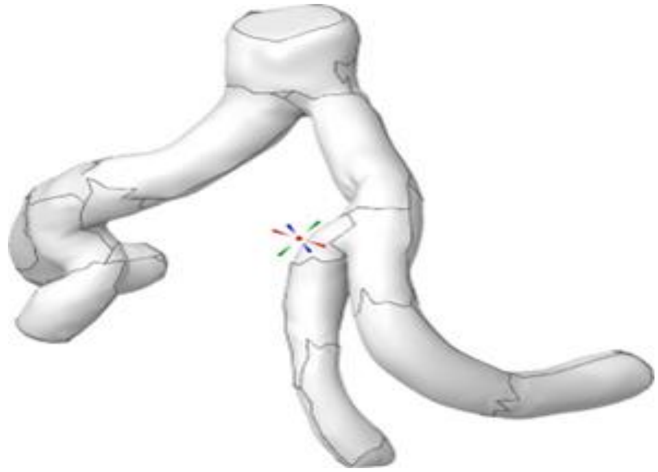


Figure 11: After facet merging

This STEP file was imported into Ansys Space- Claim 2024 R1, in which the geometry was checked and perfected. To reduce the number of triangles or facets, an intricate method of se- lecting multiple triangles on a same plane and merging them toghether to give a single plane was performed for the ease of mesh generation. Thus reducing the number of facets form around 5787 to 40. This geometry was later downloaded in SCDOC format.

In Ansys workbench, the SCDOC geometry was imported into the Fluid Flow - Meshing tool. Their were total of 2 sizing enhancements and 1 inflation procedure performed in the mesh. First sizing included defining the element size to 1 cm and second sizing involved the input of a sphere of influence with radius 20cm and element size 0.5cm. This was necessary because the overall cell count of the mesh was exceeding the maxi- mum limit of cell count of Ansys Student which is 1048567 number of cells, the centre of the sphere of influence was taken as the centre of a newly defined cartesian/coordinate system which stood between the two major branches of the iliac bifur- cation. Inflation was used to define the boundary, inlets and outlets of the fluid domain. After all this, the mesh was generated and was ready for CFD simulation.

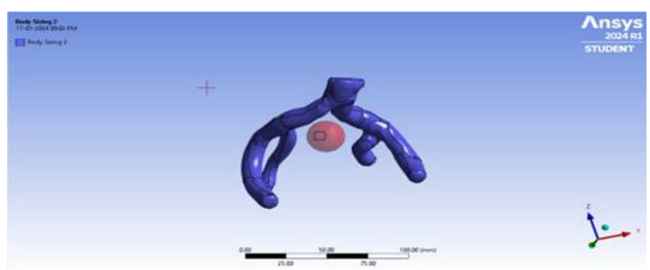


Figure 12: Sizing of the sphere of influence to reduce cell count

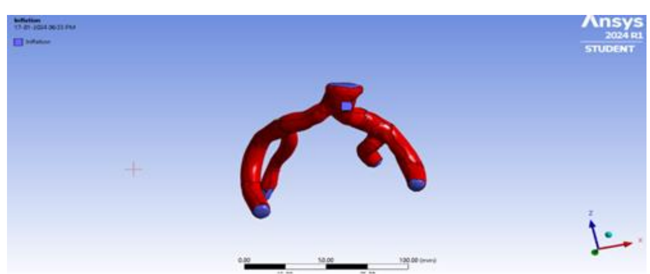


Figure 13: Defining parts of the fluid domain like inlet and outlet using inflation segments

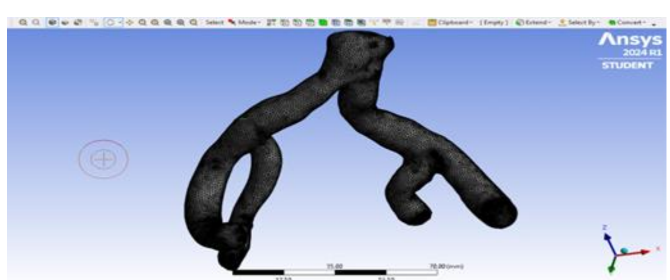


Figure 14: Generated mesh of iliac bifurcation

The subsequent phase involved defining the physics for simulation within the Ansys Fluid Flow (Fluent) Parallel Fluent environment. This commenced with the rigorous characterization of blood and its pertinent properties, encompass- ing density (1060 kg/m3), specific heat (1006.43 J/kgK), thermal conductivity (0.0242 W/mK), and viscosity (1.7894e-05). These values were meticulously derived from an extensive analysis of blood properties documented in diverse medical journals. Inlet and outlet conditions were estab- lished, incorporating boundary conditions from named selections acquired during the pre-meshing inflation process. In the inlet, the temperature was stipulated at 310K, coupled with a veloc- ity magnitude of 0.3 m/s. Hybrid initialization facilitated the commencement of physics setup calculations, furnishing the requisite framework for simulation. The solution gave the real-time visual representation of the velocity streamline of blood flow, pressure contour on the arterial wall and Eddy's viscosity.

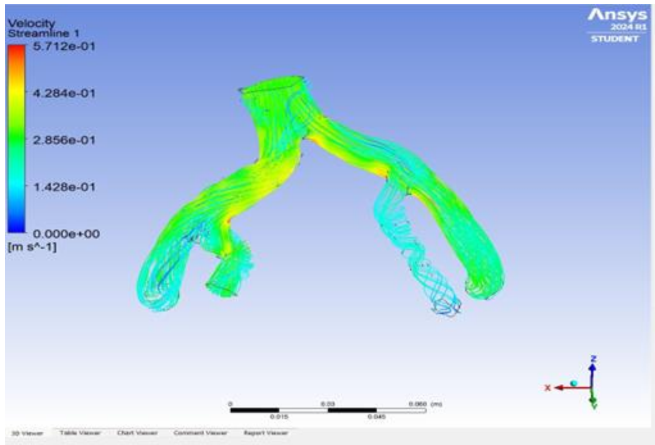


Figure 15: Velocity streamline demonstration

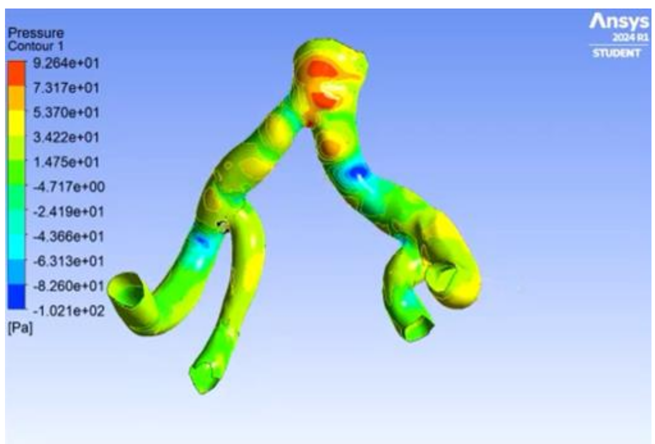


Figure 16: Pressure contour across arterial wall

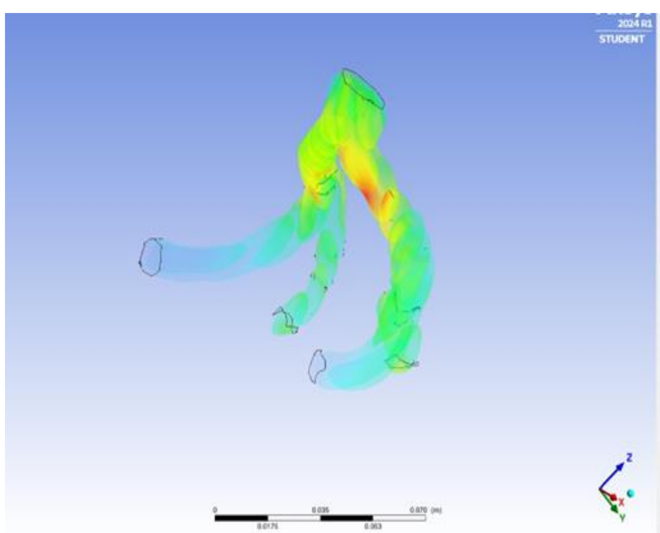


Figure 17: Eddy's viscosity in volume of abdominal aorta

Notably, the simulation solver settings introduced a pioneering element, wherein the mLR model's direct outcomes governing the abdominal aorta's expansion rate were implemented. This dynamic model, facilitated real-time alterations in the size

Number of Machines	1
Number of Cores	1
Case Read	17.152 seconds
Virtual Current Memory	1.73012 GB
Virtual Peak Memory	1.75006 GB
Memory Per M Cell	1.31058

Figure 18: Computational Expense of the Simulation and geometry of the abdominal aorta, concur- rently revealing prospective rupture locations through pressure contour analysis.

The fundamental mathematical governing equations that solved the simulation are the following;

- Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0$$

Where; ρ is density; ∇ is vector differential operator; $\frac{\partial \rho}{\partial t}$ is rate of change in density.

- Navier Stokes Equation:

$$\frac{dv}{\quad} + \frac{1}{V} \cdot (\rho v \; v \; v) = - \quad \frac{1}{\quad} \nabla p \; + \mu \nabla 2v + f$$

Where; v is the velocity of the fluid; t is time; ∇ is gradient of the pressure; μ is fluid's resistance to flow; f is external force acting on the fluid.

The computational complexity of the model was impressively low because of the geo- metric correction's and facet merging's per- formed. The simulation was able to sustain the accuracy and run smoothly of a nor- mal Laptop with integerated Radeon Vega 7 GPU and a Ryzen 5 5600H 12 core CPU along with 16 GB of DDR4 RAM clocked at 2800 mHz.

Numerical Model Utilizing Biomechanical Properties and Geometrical Variables to Approximate the Expansion Rate

Aim - The aim was to create a mathemati- cal model that could forecast the rupture date, expansion rate, and enlarged size of the abdominal aorta based on statistical data that is bio-mechanical parameters and geometrically studied variables.

Upon a comprehensive examination of the biome- chanical aspects pertaining to the Abdominal Aorta and the systematic elucidation of specific biomechanical determinants influencing Abdomi- nal Aortic Aneurysm (AAA) rupture, a formula- tion has been devised for the computation of the augmented dimensions of the abdominal aorta fol- lowing a time interval denoted as 't'. Through nu- anced adjustments, this formulation enables the calculation of the expansion rate of the abdomi- nal aorta, facilitating the prognostication of the potential rupture date. The paramount biome- chanical factors incorporated into the model iCompliance – The ability of the arterial wall to expand and increase in volume in response to rising transmural pressure.

Poisson's Ratio – The ratio of transverse contraction to longitudinal extension strain.

Elastic Modulus – The measure of a material's resistance to deformation.

Laplace's Law – States that arterial wall tension is proportional to the vessel radius for a given blood pressure in- clude:

Where; Vd is diastolic volume; Vs is systolic volume; Ps is systolic pressure; Pd is diastolic pressure.

Numerical representation of Poisson's ratio (V):

$V = -detrans / deaxial$

Where; detrans is the transversal strain and deaxial is the axial strain.

Numerical representation of Elastic Modulus (E):

λ = stress / strain

but in the case of arterial environment;

$E = (2VoRav(1 - v^2)) / hC$

Where; Vo is volume, Rav is radius, v is Pois-

son's ratio; h is arterial wall thickness and C is compliance of arterial wall.

The variables in the formula are geometrical basis of abdominal aorta, which are obtainable from the previously mentioned steps. The following is the derived novel formula:

$$x = \frac{y \Delta p l \dfrac{2 V_o R_{av}\left(1 - \frac{lou}{dol}\right)^2}{\Delta V h} + p l}{\Delta p \left[\dfrac{2\ \ o R_{av}\left(1 - \frac{lod}{dol}\right)^2}{\Delta V h} \right]} \qquad (1)$$

Where;

x = expanded diameter after 1 second of time; y = diameter before 1 second of time;

Vo = diastolic volume;

Rav = diastolic radius;

lo = systolic lateral length; l = diastolic lateral length; d = diastolic axial length; do = systolic axial length; h = wall thickness;

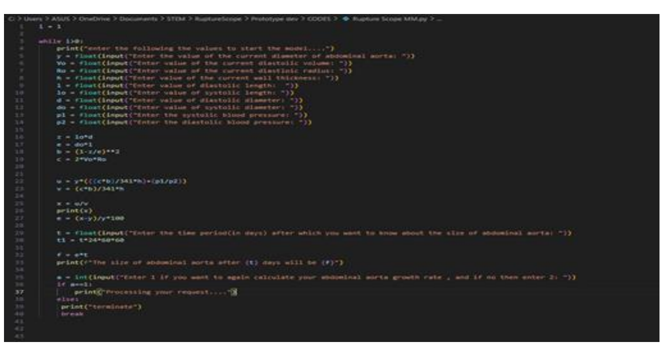
p = blood pressure mean

Upon the multiplication of the variable de- noted as 'x' with the temporal interval, expressed in seconds, the resultant product yields the diameter magnitude subsequent to the stipulated

By dividing the temporal parameter into this product, the expansion rate—expressed as growth per unit time—can be determined. Given the chronic nature of abdominal aortic aneurysm (AAA), the recommended unit for measuring expansion is "growth/year."

By analyzing the arterial wall thickness (h) and its correlation with diameter, it is possible to make temporal predictions regarding potential rupture events. A mathematical model has been implemented in Python to facilitate computational analysis. Regular inclusion of blood pressure (p) as an input helps mitigate inaccuracies caused by variable factors. It is essential to note that the Python script requires real-time blood pressure values before generating results.

To assess model efficacy, computed tomography (CT) scans were obtained from the publicly accessible 3D Embodi repository. Geometric analysis, performed using Vascular Modeling Toolkit (VMTK), was employed to extract variable values. Below are five key experimental outcomes.



```
i = 1

while i>0:
    print("enter the following the values to start the model....")
    y = float(input("Enter the value of the current diameter of abdominal aorta: "))
    Vo = float(input("Enter value of the current diastolic volume: "))
    Ro = float(input("Enter value of the current diastolic radius: "))
    h = float(input("Enter value of the current wall thickness: "))
    l = float(input("Enter value of diastolic length:  "))
    lo = float(input("Enter value of systolic length: "))
    d = float(input("Enter value of diastolic diameter: "))
    do = float(input("Enter value of systolic diameter: "))
    p1 = float(input("Enter the systolic blood pressure: "))
    p2 = float(input("Enter the diastolic blood pressure: "))

    z = lo*d
    e = do*l
    b = (1-z/e)**2
    c = 2*Vo*Ro


    u = y*(((c*b)/341*h)+(p1/p2))
    v = (c*b)/341*h

    x = u/v
    print(x)
    e = (x-y)/y*100

    t = float(input("Enter the time period(in days) after which you want to know about the size of abdominal aorta: "))
    t1 = t*24*60*60

    f = e*t
    print(f"The size of abdominal aorta after {t} days will be {f}")

    a = int(input("Enter 1 if you want to again calculate your abdominal aorta growth rate , and if no then enter 2: "))
    if a==1:
        print("Processing your request....")
    else:
     print("terminate")
     break
```

Figure 19: Python interpretation of numerical model

To determine the model accuracy we used various metrics like Mean Squared Error (MSE), Root Mean Squared Deviation (RMSD), r-squared and adjusted r-squared. We used a python interpre- tation of the methods for increased accuracy and the following are the results we got.

Parameters (VMTK)	Numerical Model	Actual Expansion
WT - 4.25 mm ID - 3 cm BPm - 73 mm hg IL - 13 cm	0.4 mm/year	0.4 mm/year ~
WT- 3.98 mm ID- 3.68 cm BPm- 82 mm hg IL- 13.23 cm	0.8 mm/year	0.9 mm/year
WT- 2.8 mm ID- 4.8 cm BPm-74 mm hg IL- 13.3 cm	1.23 mm/year	1.28 mm/year
WT- 2 mm ID- 5.6 cm BPm- 102 mm hg IL- 13.5 cm	1.56 mm/year	1.62 mm/year
WT - 1.4 mm ID - 7 cm BPm - 115 mm hg IL - 14.2 cm	1.94 mm/year	2 mm/year~
Where;		
WT = Arterial wall thickness		
ID- Mean initial diameter		
BPm = Blood pressure mean		
IL - lateral length during diastole		

Table 1: Comparison of our numerical model and lab testing expansion rate values using real- life value sets

Metric	Mathematical Expression	Value
MSE	$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(y_i - \tilde{y}_i)^2$	0.00772
R^2	$R^2 = 1 - \frac{SS_{RES}}{SS_{TOT}} = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2}$	0.9872475401346452
RMSD	$RMSE = \sqrt{\frac{\sum_{i=1}^{N} \lVert y(i) - \hat{y}(i) \rVert^2}{N}},$	0.06276941930590088
Adjusted - R^2	$Adjusted\ R^2 = 1 - \frac{(1 - R^2)(N-1)}{N-p-1}$	0.9961525945225831

Figure 21: statistical analysis outcomes depicting high accuracy

RESULTS

Using the simulation, the real-time blood flow in the iliac arteries was simulated giv- ing us eddy's viscosity, velocity streamline and pressure contour of the aortic flow. Us- ing these factors, I were able to locate the high-stressed regions in the aortic wall which are prone to rupture. I were also able to mon- itor the structural changes in the abdominal

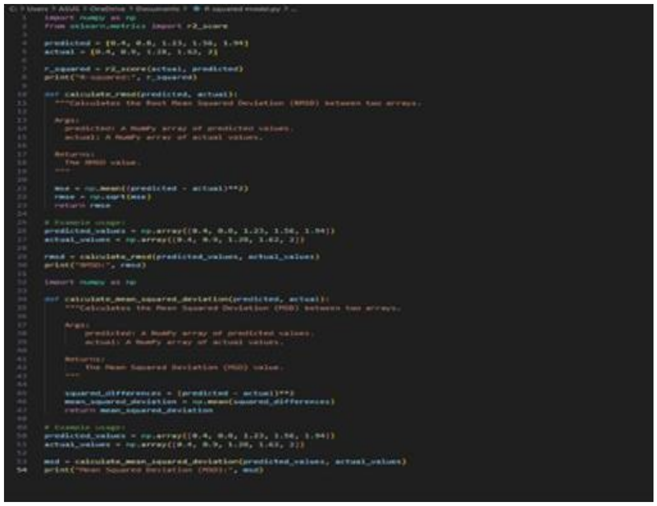


Figure 20: Python code for statistical analysis of regression model

aorta with respect to time with the aid of the simulation.

The structural changes displayed a slow increment in the mean diameter overtime and a steady decrease in the wall thickness. This was found out to be correct using the Laplace's law, a bio-mechanical law stating that diameter of a vessel is inversely propor- tional to its wall thickness i.e. as diameter increases, the wall thickness decreases.

The numerical model's overall accuracy was highly satisfying with the use of a single CT scan with respect to lab testing, which requires results from multiple imaging scans. For visual understanding of the accuracy of the model, a linear graph was plotted from the values of Table 1.

DISCUSSIONS

The Aorta Guard system integrates a parallel blood flow simulation and the model through continuous data exchange. Geometric alterations are observed by the simulation, and these values are subsequently communicated to the model's code. When coupled with an individual's blood pressure, the system forecasts the expansion rate and potential rupture date. The expansion rate is then incorporated back into the simulation, alongside the current blood pressure, facilitat- ing the visualization of size changes and identi- fication of high-stress regions in the aortic wall.

This establishes a robust and precise framework, significantly reducing fatalities associated with Abdominal Aortic Aneurysm (AAA) therapeutic procedures and enhancing procedural efficiency. The following are the ways in which Aorta guard is going to benefit the patients and doctors:

The knowledge of the date of rupture helps out in planning the surgical intervention. Currently, doctors perform human estima- tion for the prediction of expansion rate and rupture date which is mostly inaccu- rate but Aorta Guard's numerical resolves the issue by using statistical data related to the bio-mechanical properties of the specific patient's abdominal aorta making it case- specific and accurate.

As of now patients are suggested to have an imaging scan on an yearly basis giving us an average of 5-6 scans, by using Aorta Guard framework this number can be reduced to as low as 2 scans reducing the treatment cost and individual's exposure to radiation.

The knowledge of high-stressed regions will tremendously help in the planning of EVAR surgery by providing accurate measurements for stent-graft placement, thus minimizing fatalities from improper stent-graft place- ments.

Proper stent-graft placement requires de- tailed measurements of the abdominal aorta from Celiac trunk to iliac bifurcation, these are measured from imaging scans using prac- tises which have a chance of human error. Aorta Guard, eradicates this problem by au- automation on validated framework.

The surgeries are performed on the basis of diameter **benchmark of 5.5 cm, but there is a high probability** of the abdominal aorta ruptured before attaining a diameter of 5.5 cm. Hence, the accurate factor of determining the time of intervention is arterial wall thickness.

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CONCLUSION

The Aorta Guard framework represents a sophisti- cated integrative platform leveraging state-of-the- cardiothoracic surgeon, Apollo group of hospitals, Indore)

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[9] For further details regarding the project and references, contact the authors at-aadittyadeouskar7a1@gmail.com project report generated by LATEX
[10] The data regarding the patients geometry were acquired from CT Scans from open source online repositories.