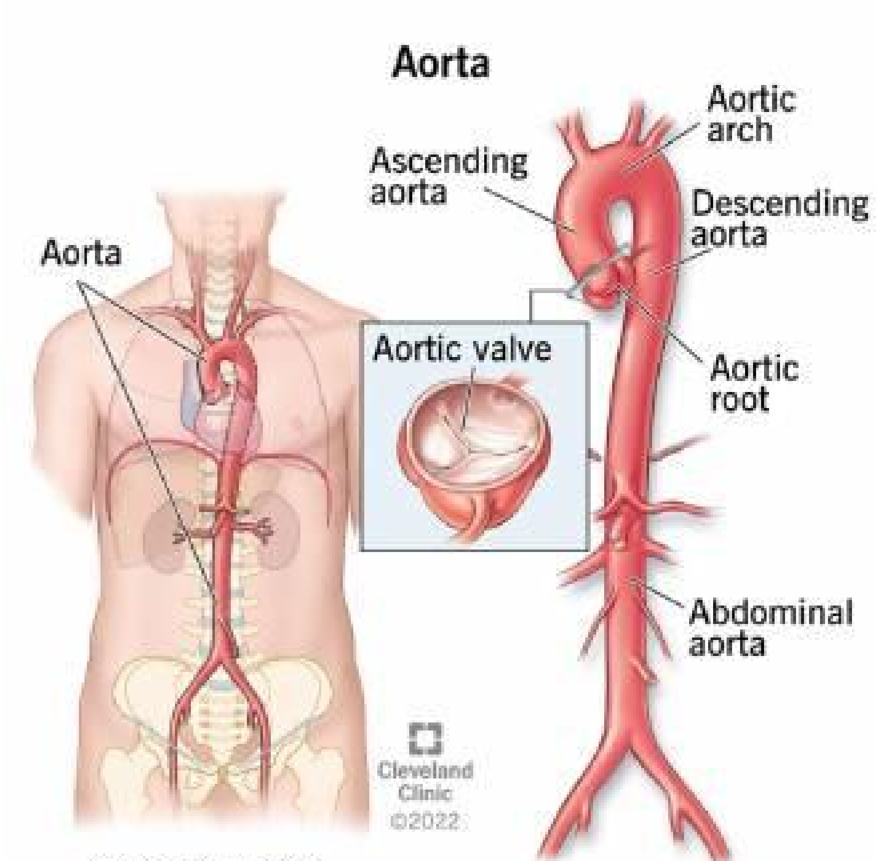
# Ascending through descending aorta with & without stent insertion

A CFD Model and Analysis by Kian Hageman

# Clinical Question

How effective are stents at restoring healthy aortic flow?

# Clinical Background




(Professional, 2025)

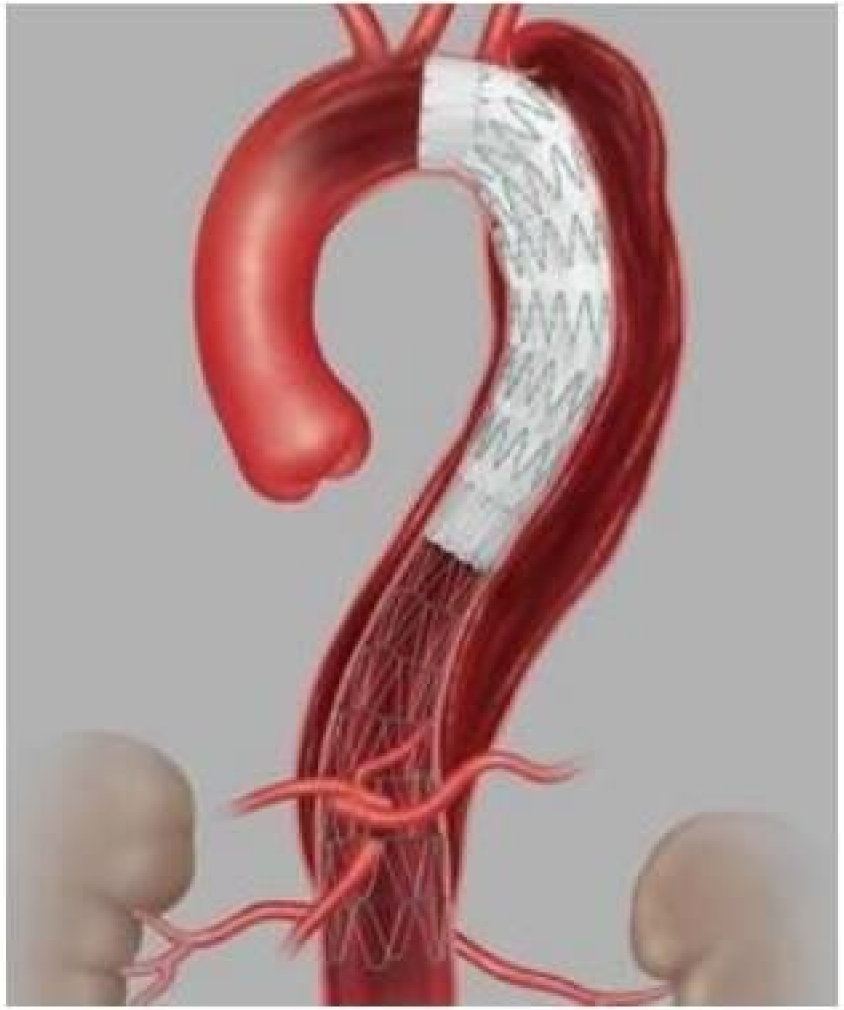
Stents are designed to restore blood flow through an artery or other vasculature to promote healthy bio transport through the vasculature system.

Typically made of metal or other stiff biocompatible materials, they are commonly placed via catheter and expanded to size by a surgeon via balloon.

Clinical indications for a stent include aortic aneurysms, dissection, coarctation, traumatic injuries, and more.

Around 600,000 stenting procedures are performed each year in the US (Carda Health, 2023).

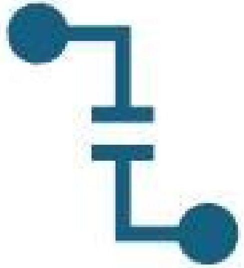
While stents can be used for anyone, they are more commonly seen in older patients.



(*Vascular Stents & Grafts*, n.d.)


Professional, C. C. M. (2025, March 19). *Aorta*. Cleveland Clinic. https://my.clevelandclinic.org/health/body/17058-aorta-anatomy
*Vascular stents & grafts*. (n.d.). Questions and Answers in MRI. https://mriquestions.com/vascular-stentsgrafts.html
Carda Health. (2023, May 3). What percent of blockage requires a stent? *Carda Health*. https://www.cardahealth.com/post/what-percent-of-blockage-requires-a-stent

# Hemodynamic Importance



## Returning to Normal Flow

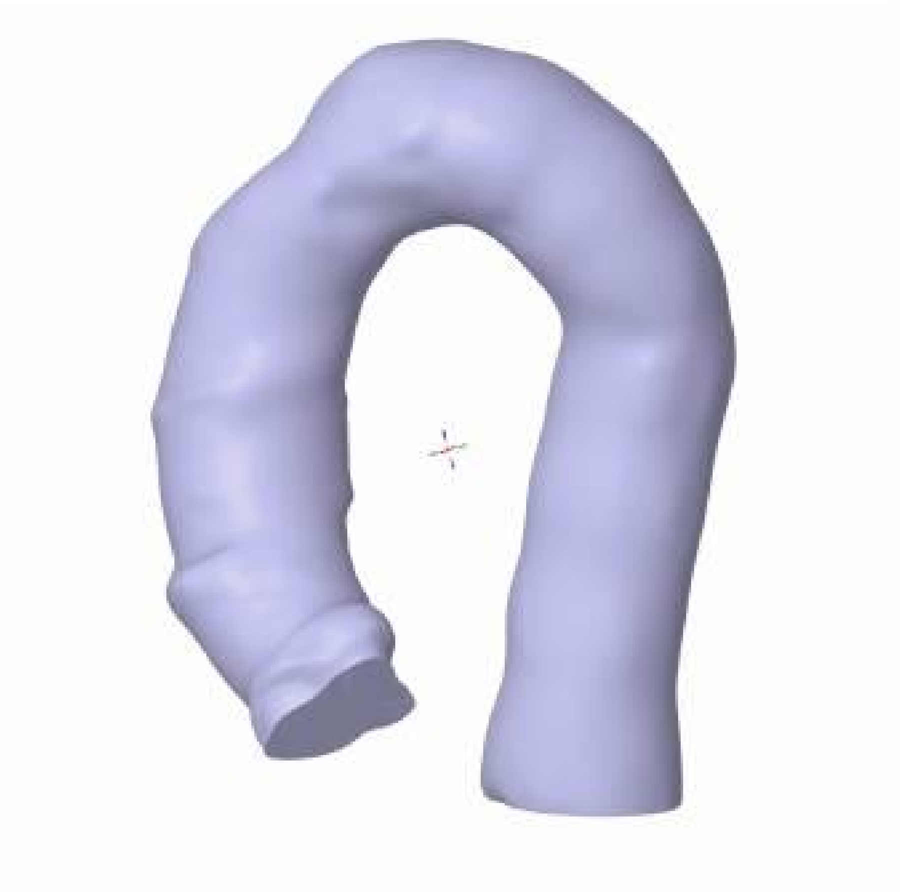
The stent causes the vasculature to re-open or provides a more streamline flow.

## Bio Transport

A blockage of the descending aorta prevents proper bio transport including biochemical signals, nutrients, cell waist return, and much more.

# Model Geometry Origin and Modification

Stented geometry was created from an anonymized patient MRI. It's important to note the roughness of the descending aorta. The video represents the internal flow of a stented artery.



Healthy geometry was created using Blender and its "smoothing" tool. The tool was dragged over the surface of the stented area until a smooth, healthy aortic artery was formed.

# Methodology- Healthy: Mesh Generation

- Figure 1 shows the mesh diagnostic summary. The key values given are the number of cells (344,156) and orthogonal quality of 0.1731.
- Figure 2 shows a cross sectional cut of the mesh that shows 10 boundary layers with a 1.2 growth rate and a poly-hexcore.
- Figure 3 and 4 show the general geometry and hexagonal surface mesh.
- While the cell count and orthogonal quality of the mesh can be improved, the mesh should be sufficient for the purposes of the study.

```
Meshing>
---------------------------------------------
Diagnostics Scope   : 1 Objects, 3 Face Zones, 1 Cell Zones
Objects             : (fff-facets)
---------------------------------------------
Volume Diagnostics :

Total Number of Faces            =    22766
Total Number of Interior Faces   =  1839239
Total Number of Cells            =   344156
Minimum Orthogonal Quality       =   0.1731
Maximum Aspect Ratio             =    26.76
Number of Isolated Cells         =        0
---------------------------------------------
```

Fig. 1

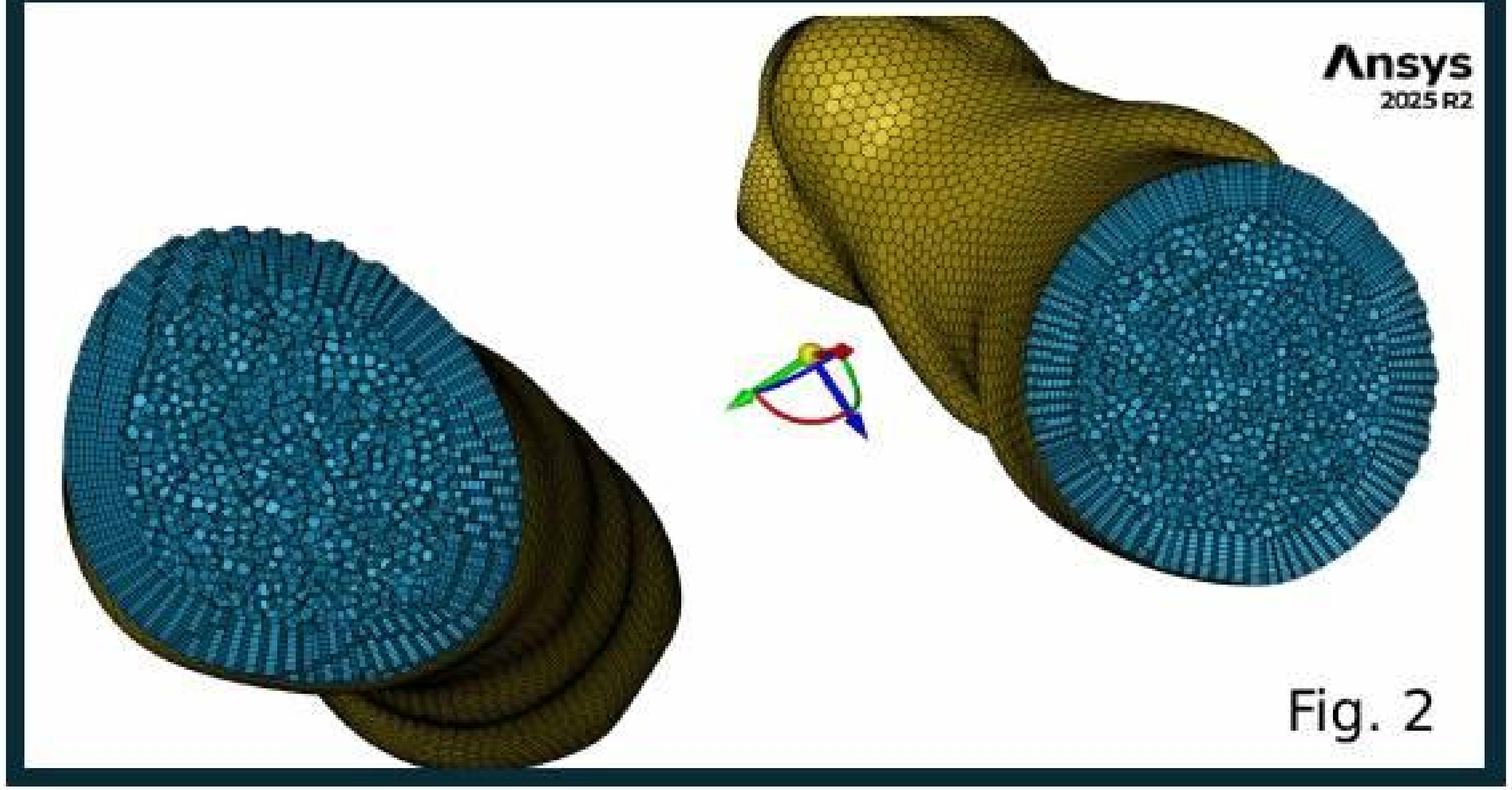



Fig. 2

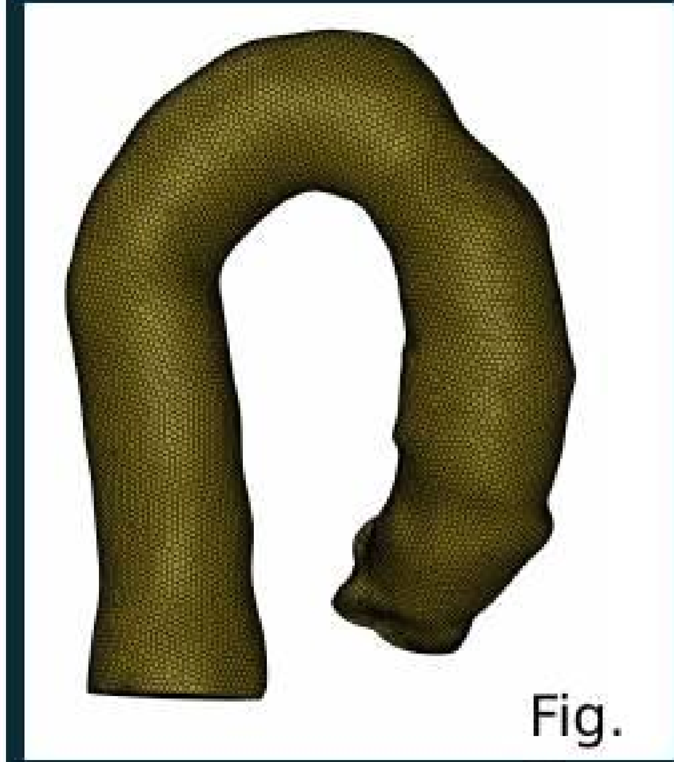


Fig. 3

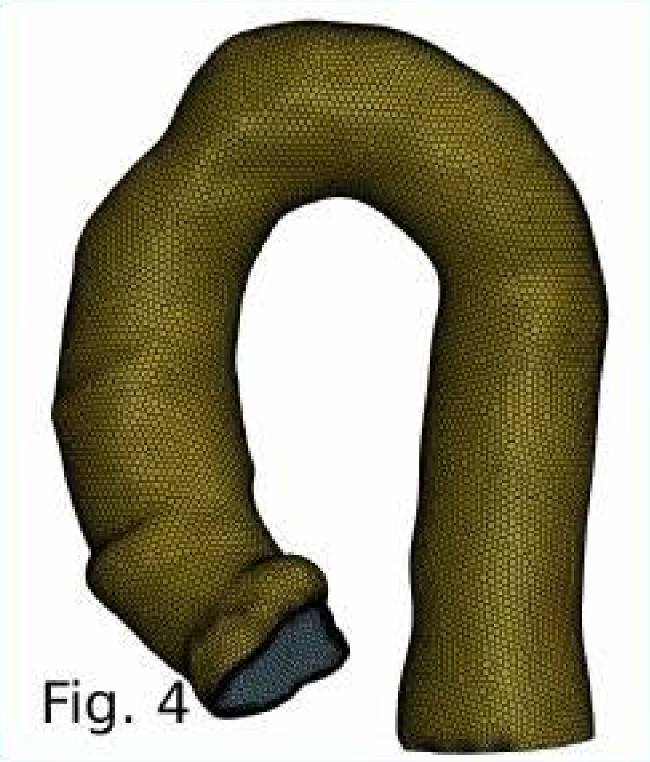


Fig. 4

# Methodology- Healthy: Calculations

- Figure 1 shows the CPU clock time and other computational metrics.
- Figure 2 shows the area-weighted average velocity magnitude over flow time.
- You can clearly see the computational time: 60 minutes.

```
Performance Timer for 18601 iterations on 8 compute nodes
  Average wall-clock time per iteration:                0.169 sec
  Global reductions per iteration:                         49 ops
  Global reductions time per iteration:                 0.000 sec (0.0%)
  Message count per iteration:                           1734 messages
  Data transfer per iteration:                         14.168 MB
  LE solves per iteration:                                  4 solves
  LE wall-clock time per iteration:                     0.062 sec (36.8%)
  LE global solves per iteration:                           2 solves
  LE global wall-clock time per iteration:              0.000 sec (0.1%)
  LE global matrix maximum size:                           50
  AMG cycles per iteration:                             5.637 cycles
  Relaxation sweeps per iteration:                        196 sweeps
  Relaxation exchanges per iteration:                       0 exchanges
  LE early protections (stall) per iteration:           0.005 times
  LE early protections (divergence) per iteration:      0.000 times
  Total SVARS touched:                                    401
  Time-step updates per iteration:                       0.02 updates
  Time-step wall-clock time per iteration:              0.000 sec (0.1%)

  Total wall-clock time:                             3142.706 sec


Simulation wall-clock time for 18601 iterations     3644.1329 sec
```

**Figure 1.** CPU clock-time and other solution matrices.

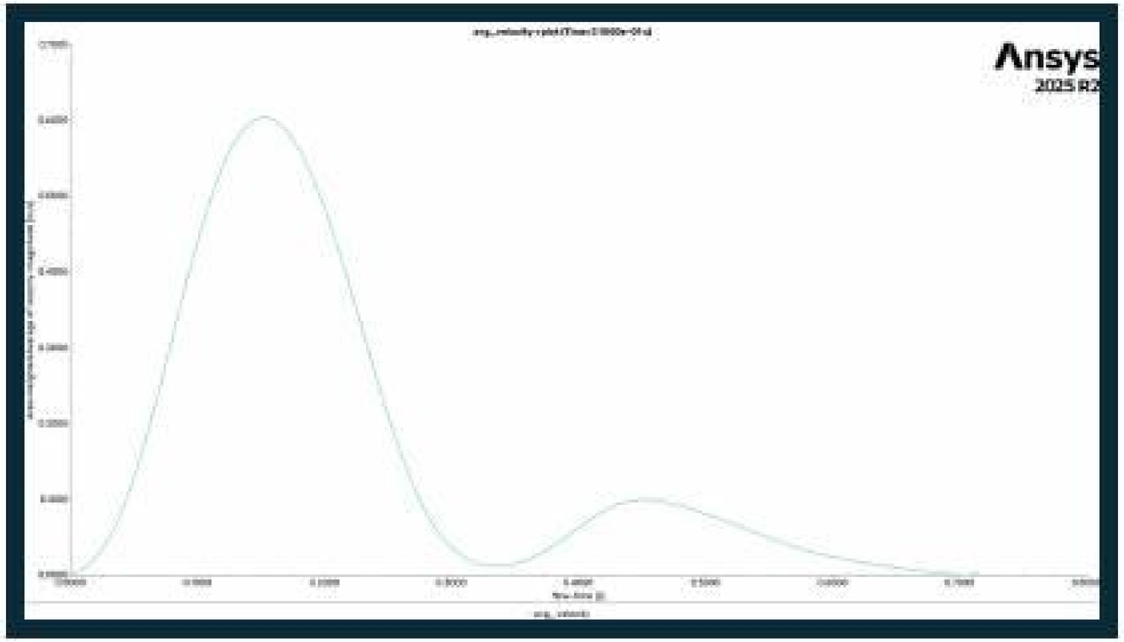



**Figure 2.** This figure shows the area weighted average velocity over the flow time from 0.0 to 0.7 seconds. This proves our cardiac cycle flow program is working correctly.

# Methodology- Stented: Mesh Generation

- Figure 1 shows the mesh diagnostic summary. The key values given are the number of cells (475,503) and orthogonal quality of 0.1451.
- Figure 2 shows a cross sectional cut of the mesh that shows 10 boundary layers with a 1.2 growth rate and a poly-hexcore.
- Figure 3 and 4 show the general geometry and hexagonal surface mesh.
- While the orthogonal quality of the mesh can be improved, the mesh should be sufficient for the purposes of the study.

```
----------------------------------------
Diagnostics Scope  : 1 Objects, 3 Face Zones, 1 Cell Zones
Objects            : (fff-2-facets)
----------------------------------------
Volume Diagnostics :

Total Number of Faces          =    33414
Total Number of Interior Faces =  2421986
Total Number of Cells          =   475503
Minimum Orthogonal Quality     =   0.1451
Maximum Aspect Ratio           =    27.16
Number of Isolated Cells       =        0
----------------------------------------
```

Fig. 1

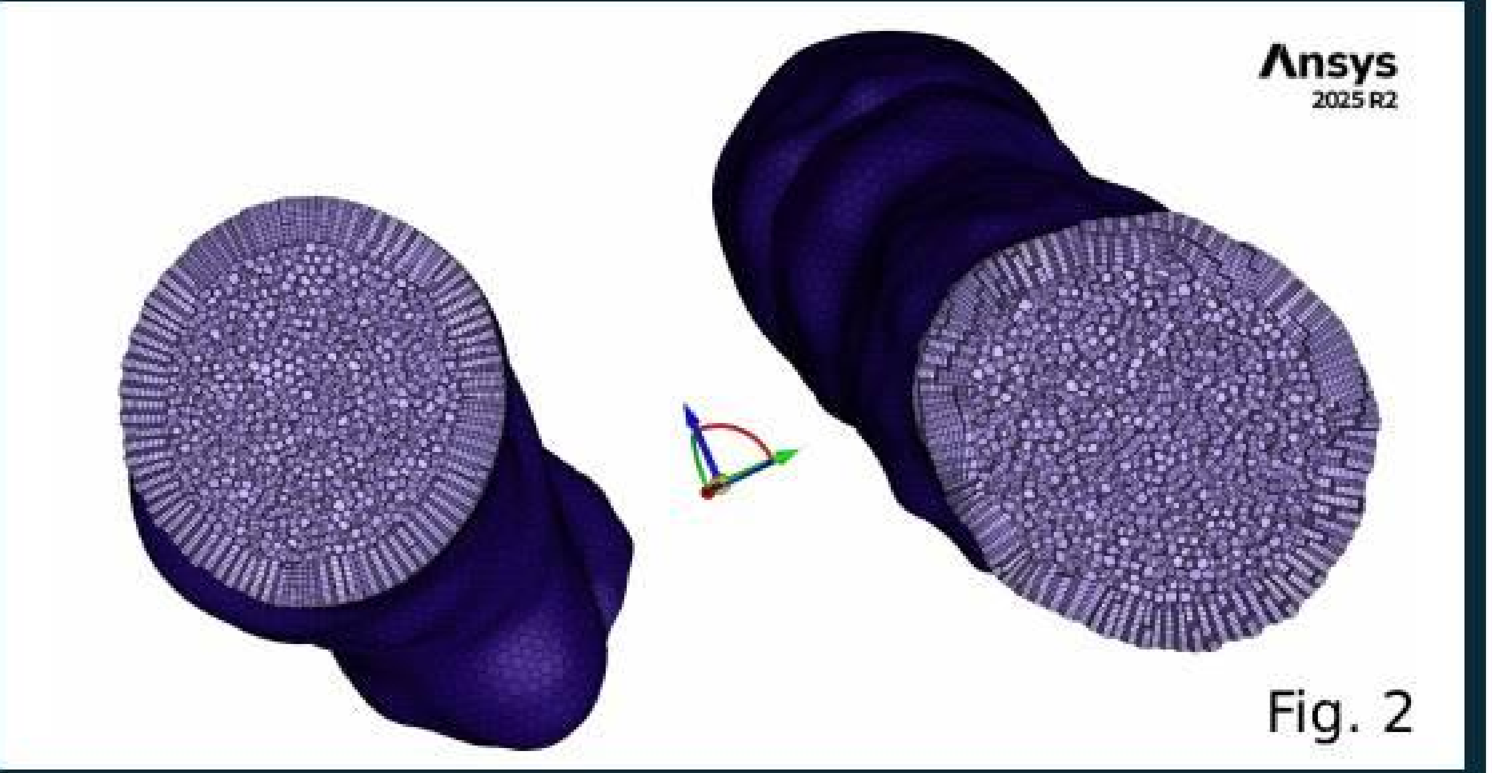



Fig. 2

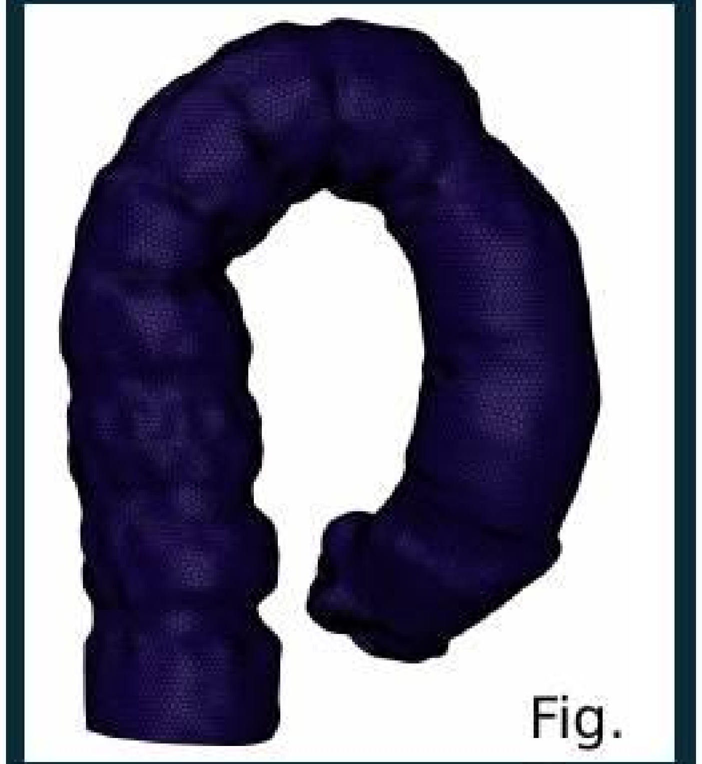


Fig. 3

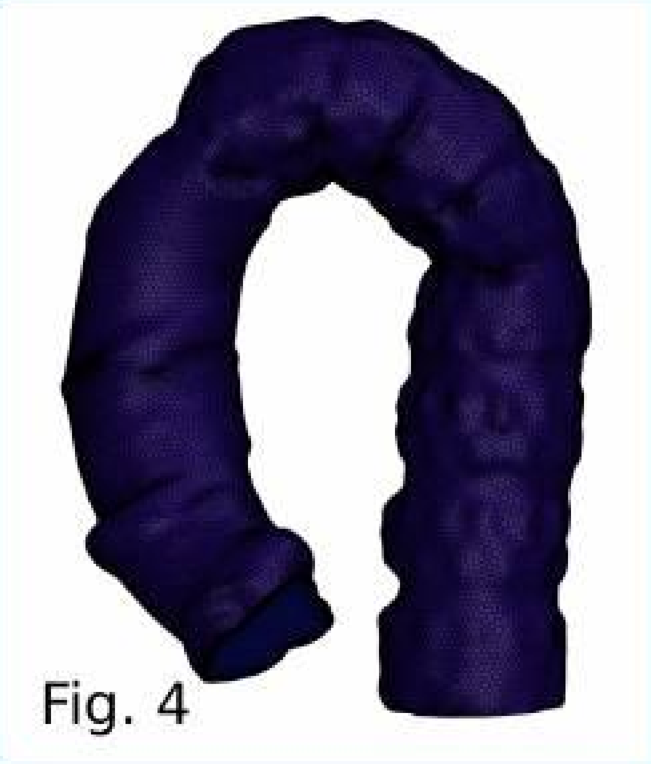


Fig. 4

# Methodology- Stented: Calculations

- Figure 1 shows the area-weighted average velocity magnitude over flow time.
- Computational time: 60 minutes.
- CPU usage and exact time were not captured.

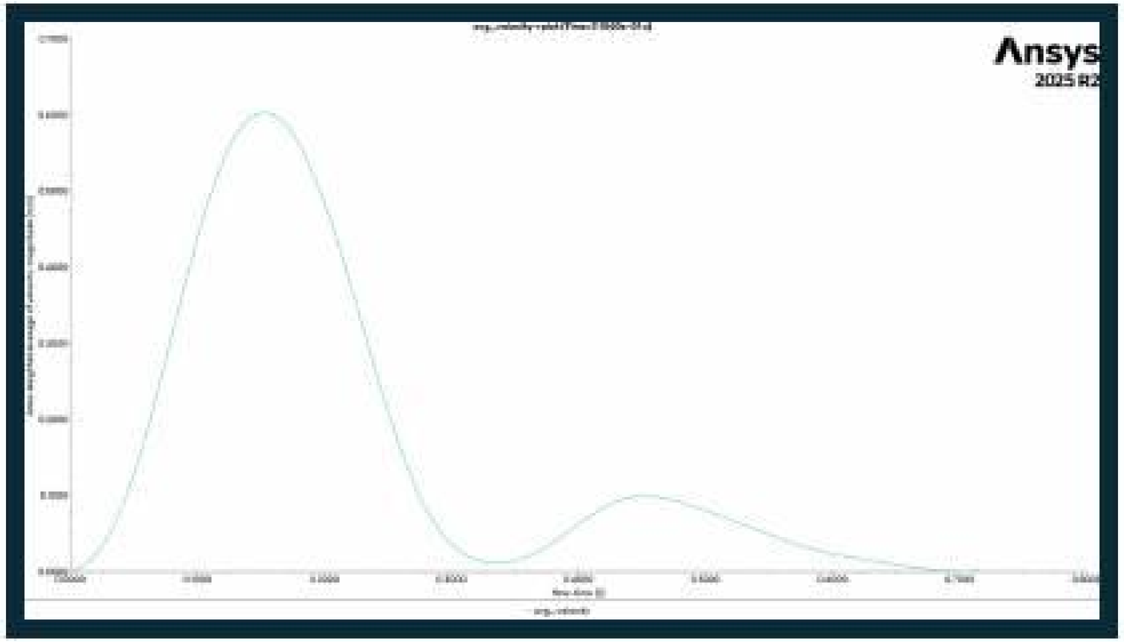



**Figure 1.** This figure shows the area weighted average velocity over the flow time from 0.0 to 0.7 seconds. This proves our cardiac cycle flow program is working correctly.

# Visualization of Flow Fields: Full Body

Figure one to the right shows 4 15*15 grids of particles and the path those particles take over the simulation. This is a representation of the overall flow in the blood vessel. Note the high velocity of the particles throughout the entire geometries for both the healthy and stented models.

## Key Points:

- It’s important to note that, overall, the difference in velocities of the stented vs. healthy aorta section is comparably similar. This suggests that while the stent is in place, the overall flow profile can be restored.
- In this study, I would like to more closely focus on how the change in geometries between the stented and healthy aorta differ. Seeing the change in direction of some particles that then create recirculation pockets within the stented regions in important.
- It is also good to note the turbulent flow  created by the ascending aorta.

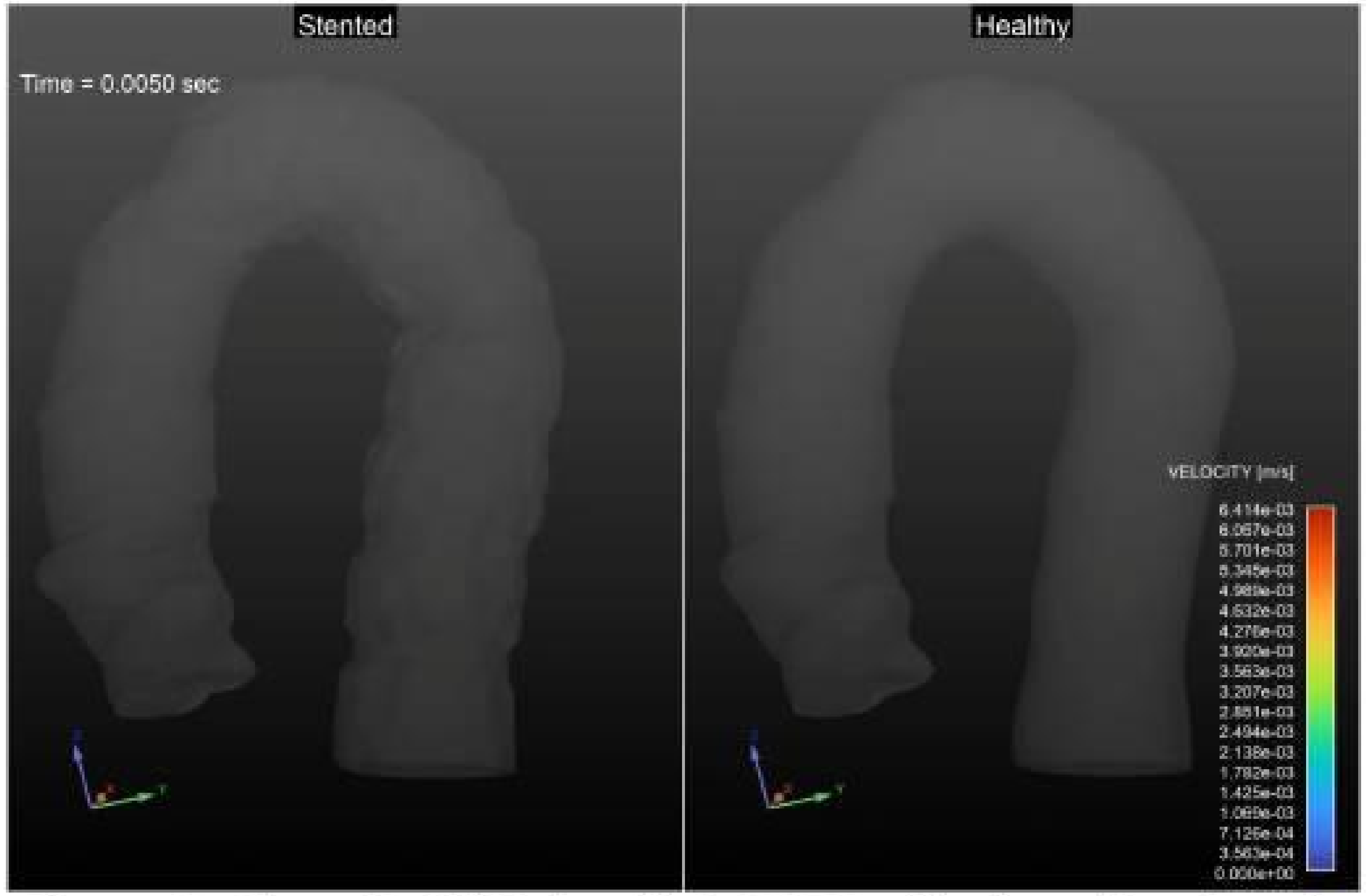



**Figure 1:** Shows the full body with 4  15*15 grids of particles placed right after the aortic valve, halfway up the ascending aorta, at the top of the aortic arch where the stent starts, and midway down the stent to show how the fluid flows around the region.

# Visualization of Flow Fields: Stenosis Focus

A zoomed in look at the stented region provides a greater understanding of how the stent effects the fluid flow through the aorta.

Key Points

- Note the recirculation happening in both healthy and stented geometries; however, the recirculation in the stented aorta is significantly higher than that of the healthy aorta.

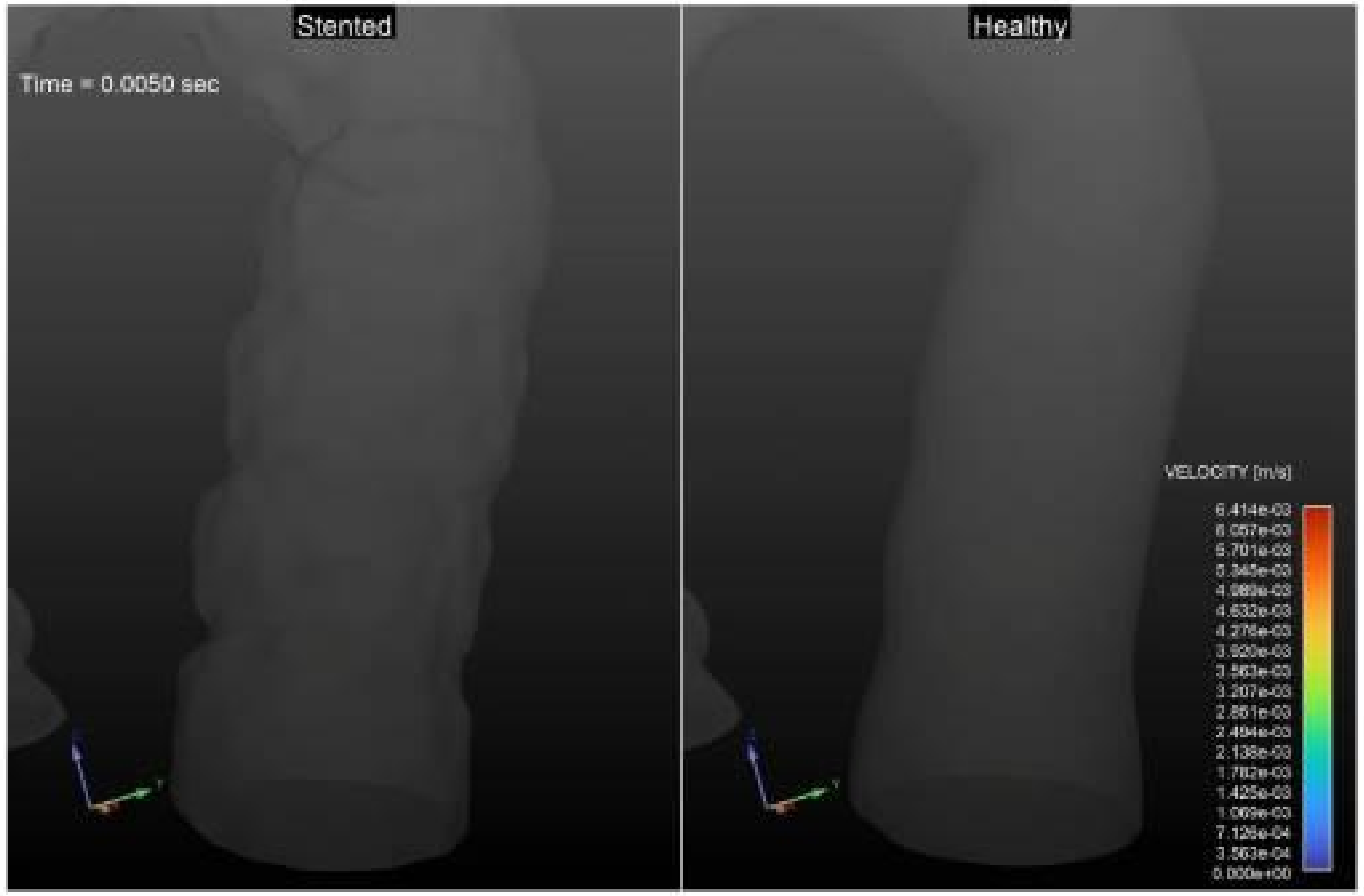
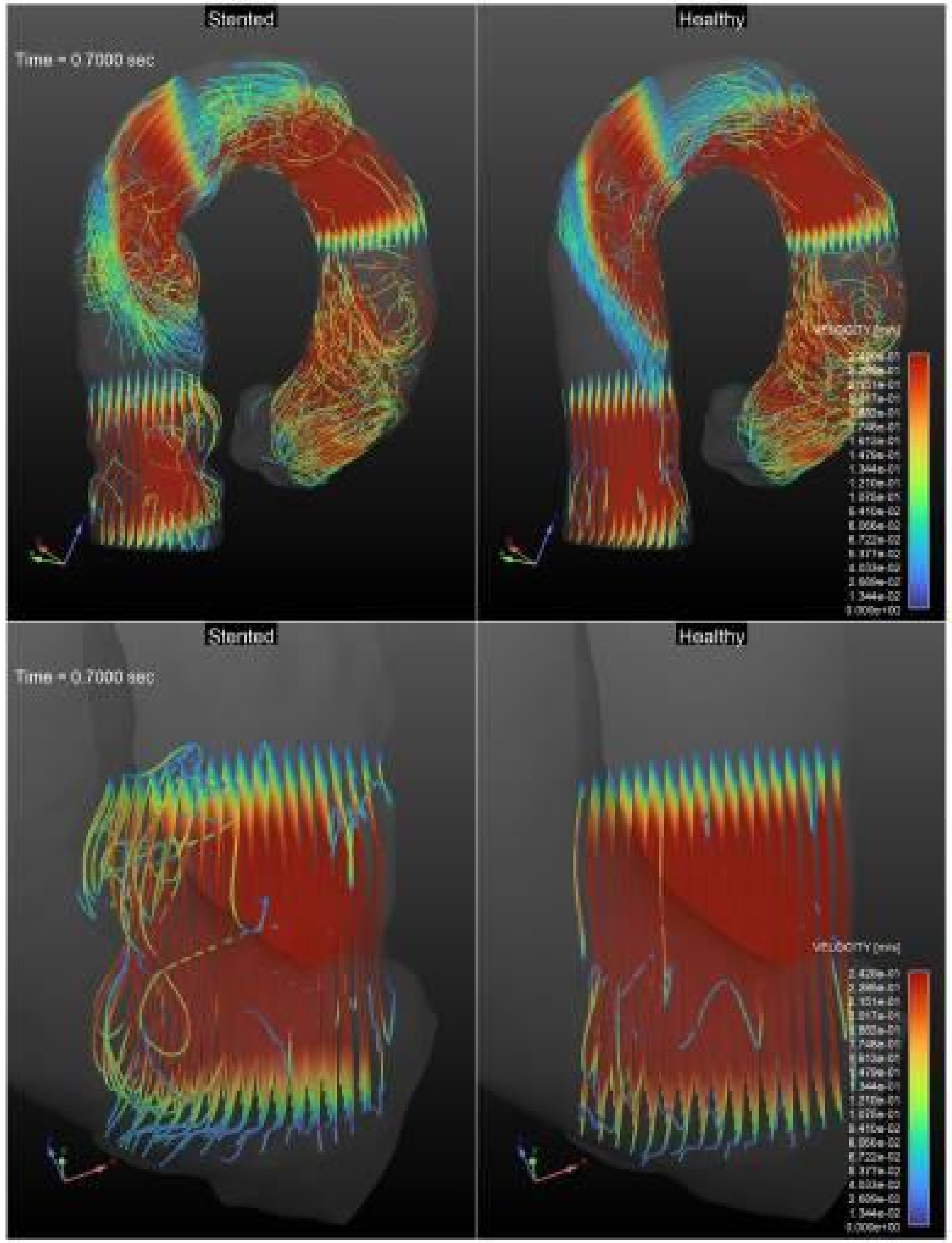



**Figure 1:** Shows a zoomed in view of the stent with a flow grid starting at the midpoint of the arch and one halfway down the stented region. The velocities of the particles are noted by color and conical arrow heads to allow for a better visualization of their direction.

# Visualization of Flow Fields: Tubes

The images to the right show the particles pathway colored by the velocity. These images allow for a better visualization of the recirculation occurring during the ascending aorta and how the stented wall geometry causes recirculation pockets to form.

**Figure 1:** The top figure shows the entire geometry with four sets of 15*15 grid particle pathways created to visualize the recirculation through the artery. The bottom figure shows a zoomed in portion of the descending aorta with and without a stent. For both the stented geometry is on the left.




## Key Points

- The bottom figure shows how the fluid is still flowing quickly and smoothly, particularly around the centerline. However, relative to the healthy geometry the recirculation pockets created by the stent do create flow disruption.
- The top figure shows the seemingly chaotic flow paths created by the angle of inlet and curved geometry of the ascending aorta.
- Both figures show how the stented geometry is still pushing high flow velocities around the centerline.

# Cross Sectional Pressure distribution

Figure one to the right shows the cross-sectional pressure at the end of the cardiac cycle. The visual shows the relatively uniform pressure distribution over each cross-sectional area with the greatest pressure being at the end of the stented descending aortic region.

## Key Points

- Disappointingly, this visual tells us nothing we do not already know. It is additionally confusing given the best viewing angle does not accurately portray the flow of fluid time well.

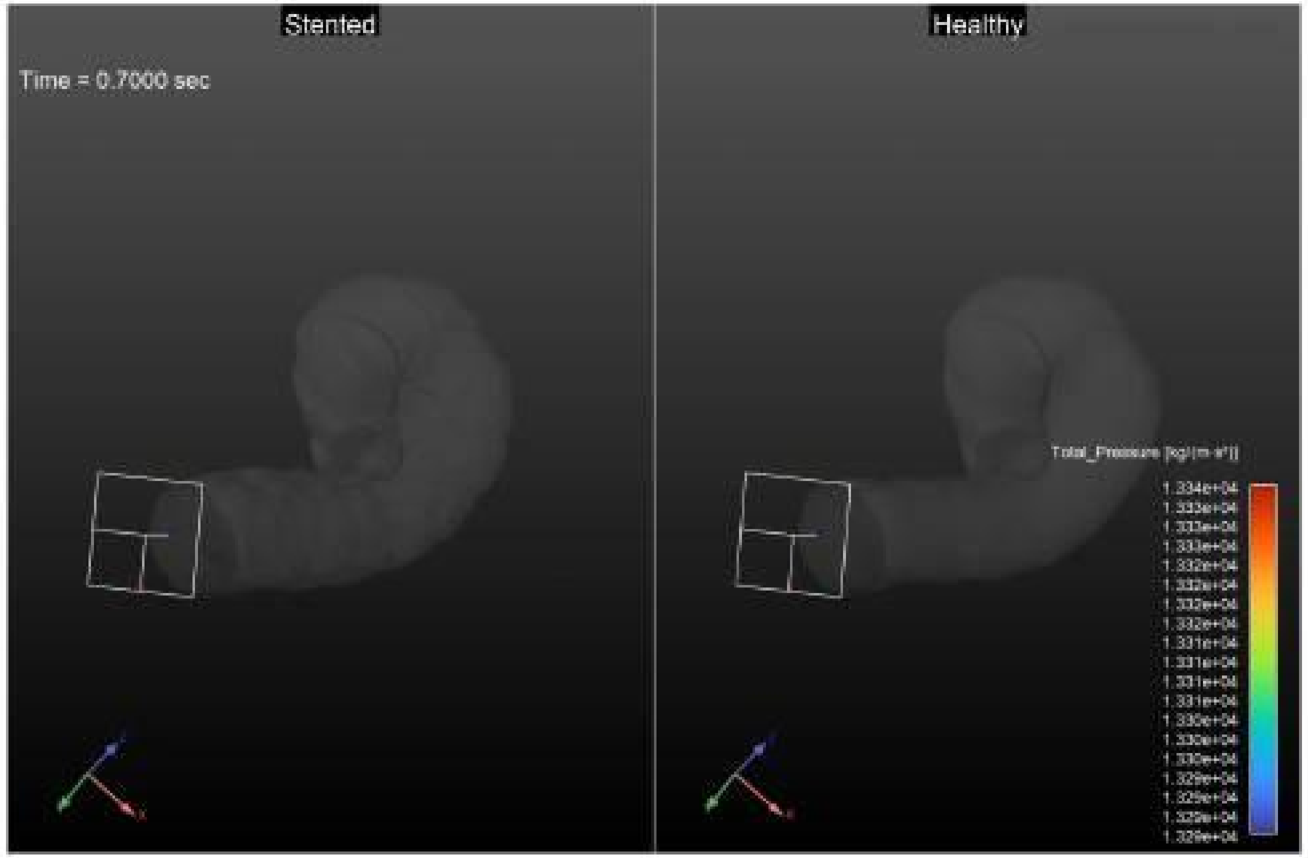



**Figure 1:** Displays the pressure distribution. This graphic does not show anything important to the study in question.

# Wall Shear Stress Patterns

Figure one shows the shear wall stress over the cardiac cycle. Red regions correlate to high stress levels. When looking at the wall shear stress it is important to look at the midpoint of the aortic arch through the model's descending aorta where the stent is placed.

Key Points

- As the cardiac cycle moves along the aorta you see the stent producing high stress regions due to its relatively rough geometric features, creating pockets of high stress for each ridge. While the stent may provide improved flow through the region, relative to the healthy aorta there are significantly higher stress occurring over the sten
- It is important to point out the high stress point created following the inlet and that produced by the stent placement are not equal.

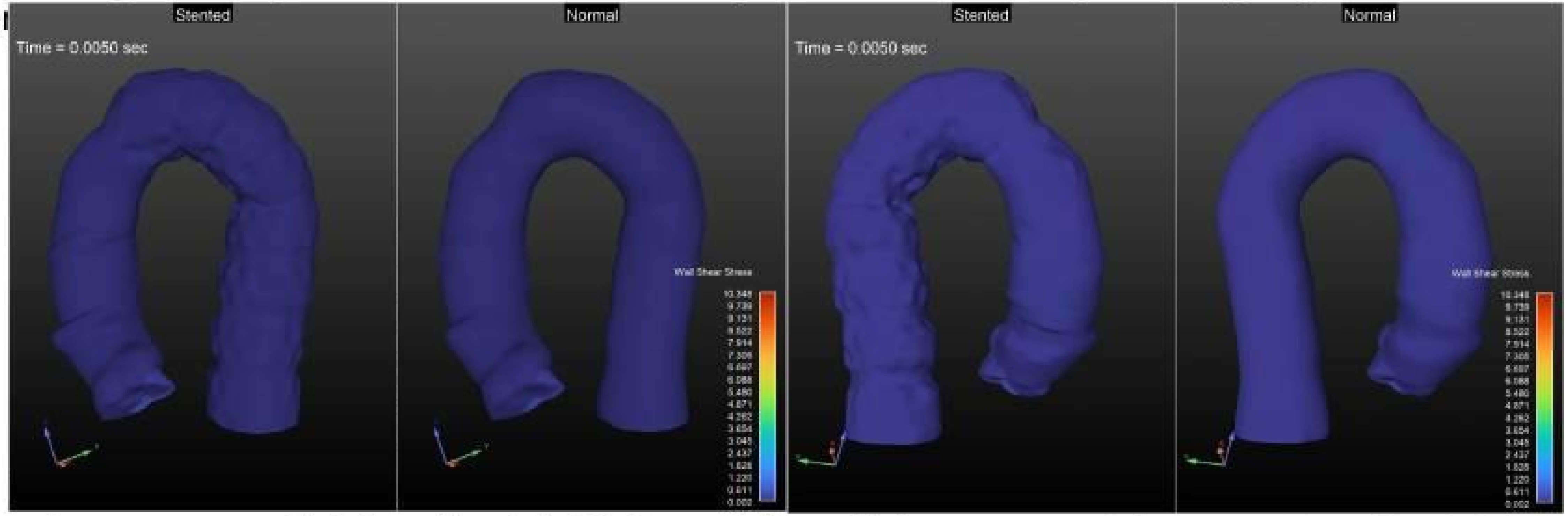



**Figure 1:** Front (right) and back (left) views of the wall shear stress of the aorta. From time 0.005 to 0.700 seconds, the video covers a full cardiac cycle, stress is colorized over the extrema of the calculated stress.

# TAWSS

Time Average Wall Shear Stress (TAWSS) shows the areas under constant stress in the artery. The high stress areas are shown in red and represent the areas most likely to experience plaque build up and other adverse health effects.

## Key Points

- Areas where the stent and arch regions overlap are experiencing the highest consistent stress over the cardiac cycle. These areas are experiencing higher stress levels than their downstream stented counterparts. This is most likely caused by the turbulent flow from the inflow angle and curved geometry in the ascending aorta.

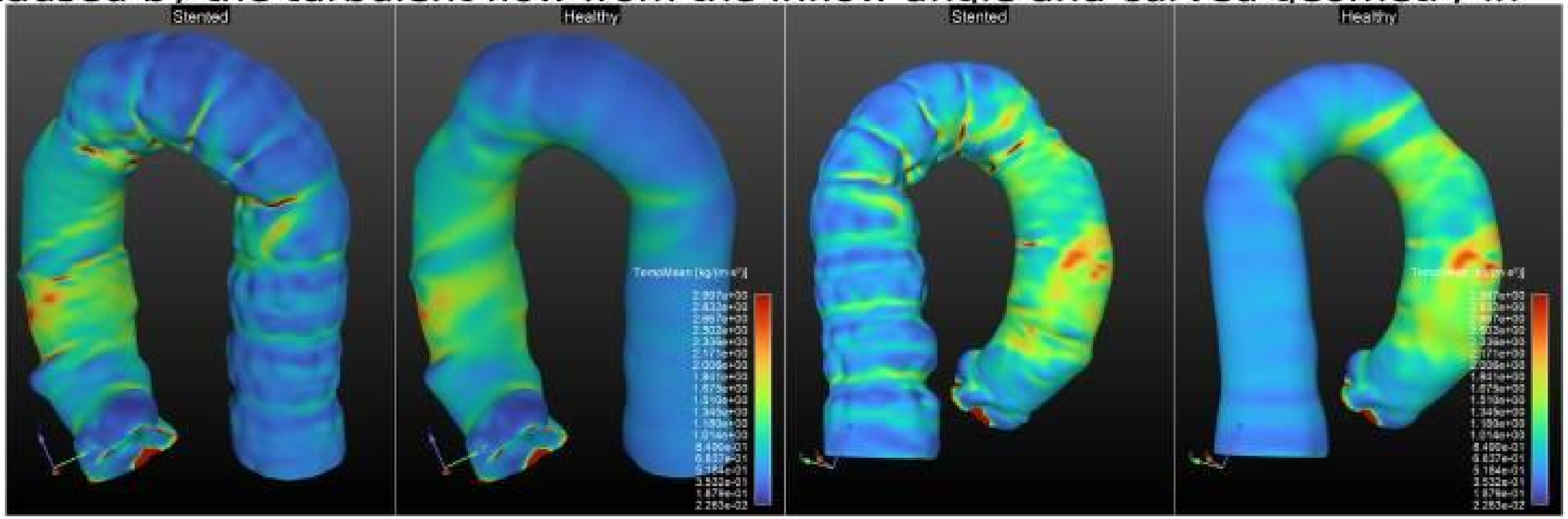



**Figure 1:** Shows the Time Average Wall Shear Stress (TWASS). This averages the wall shear stress over the entire cardiac cycle. The two angles shown allow for a full visualization of the model (I could not get the rotation along the z-axis to work) looking at the XZ plane with a positive and negative Y view.

# OSI

Oscillatory Shear Index (OSI) represents the reversal of flow around the walls of the artery. This is critically important to note as it represents places that plaque can settle, clump, and grow.

Key Points

- It is important to note the areas of high oscillation are created by the stent causing a rough, patterned texture in the wall. This pattern creates pockets of recirculation as seen in the visualization of the flow fields.
- Noticing the healthy geometry has remnants of the same oscillatory behavior. While this may be due to a natural oscillatory behavior.
- More probably, it is a flaw caused by how the healthy geometry was created. The smoothing of the stented geometry may not have been sufficient. The significance of this error is unknown.

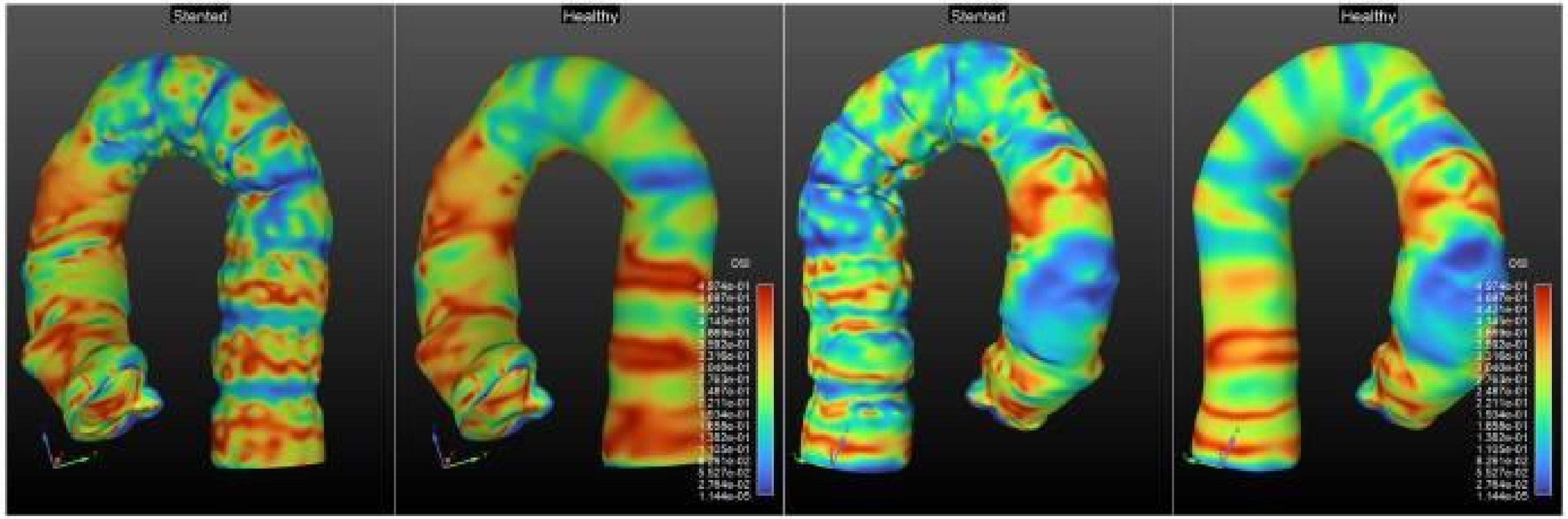



**Figure 1:** Shows the Oscillatory Shear Index (OSI). OSI is how much the shear direction oscillates through the tube. This represents flow reversal along the walls of the tube. High OSI events are red in the image. It is ca n:

$$\mathrm{OSI} = \frac{1}{2}\left(1 - \frac{\left|\int_0^T \tau_w(t)\,dt\right|}{\int_0^T \left|\tau_w(t)\right|\,dt}\right)$$

# Clinical Implications

- Significant hemodynamic differences and similarities between stented and healthy aortic arteries
  - The biggest differences created by the stent are recirculating pockets created by the stent geometry. These pockets create regions of recirculating flow, causing high wall shear stress and large oscillating shear indexes.
  - The increase in stress and oscillation can cause already damaged or sensitive aortic walls to have buildup around and in the stented regions.
  - Further studies of the effects of stents on flow should be conducted. Given the calculations completed and visualization of the flow field, it is unclear if these recirculating pockets create a truck-bed like effect. Where the recirculating, fluid causes a boundary to form as the fluid moving past the pocket is too fast and “bounces” or is blocked from entering the recirculation pocket.
- Flow metrics providing the best insights for device development and design
  - WWS provided good insights as to the stress load of the artery caused by the placed stent.
  - OSI graphic allows for a clearer understanding of the recirculation pockets and exposes the potential flaw of the healthy geometry, throwing into question the accuracy of the model.
  - The visualization of flow fields and their ability to show that centerline flow is still moving fast and through the region, proving the stent is in fact doing its job.
- CFD simulations and device design
  - This simulation study is a great example of how a CDF model can be used to better understand how the devices we design interact with the body and its functions. These simulations can improve pre-trial understanding of expected device improvements.

# Discussion

## Key Learnings

- Stents are amazing feats of biomedical engineering; however, they can still be improved. Reductions in high stress regions as shown in this study should be looked into and further testing should be conducted.
- The importance of creating good enough yet not too complex CFD models has become more apparent during this project.
- The use of MRI/CT/X-ray medical images to create patient-specific geometries was a great experience.
- The understanding that the smoothened model that was created in Blender to represent our healthy model may not be completely accurate.

## Future work

- Create better flow field visualization to see particles that better stick to centerline flow patterns or bounce back to centerline, not having a zero-velocity wall, should be interesting.
- Interesting to see how you could layer a hydrogel into the recirculation pockets the stent creates to help reduce the stressing effects and you could incorporate drug delivery.
- Further studies covering how these recirculation patterns are formed, and if they resemble the “truck-bed” problem that pickups experience would be very interesting.