Radiel Health (Team 15)

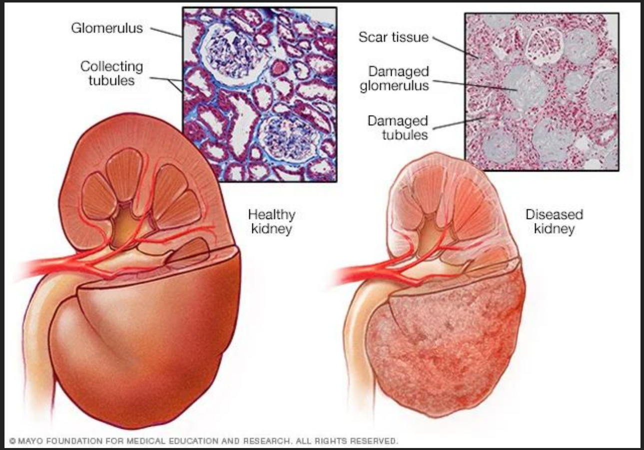
Rishabh Sharma, Nicholas Jiang, Sarvesh Sivakumar

Table of Contents

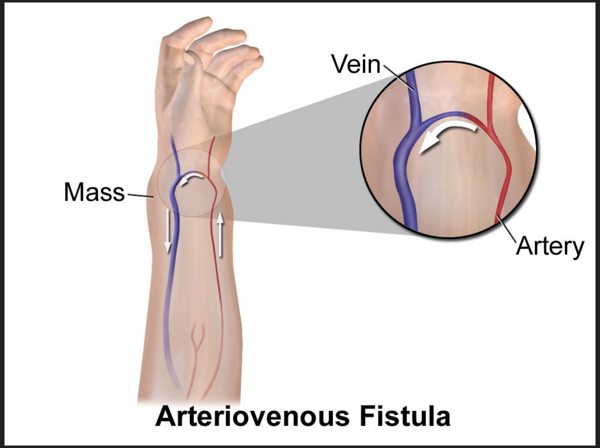
Medical Background

Kidneys

- Key Roles of the Kidneys
  - Filter waste and excess fluid from blood into urine
  - Regulate blood pressure via hormone (renin) production
  - Stimulate red blood cell production and activate vitamin D.
- Why Kidneys Fail
  - Diabetes and high blood pressure are the top culprits
  - Inflammatory Damage and Genetic causes
  - Acute injury from sepsis, toxins or obstruction
- Impact
  - 1 in 10 Canadians and 1 in 7 Americans have Kidney Disease
  - Once Kidney Disease gets to the final state, Kidney Dialysis is needed
  - Over 500 000 Americans are on Kidney Dialysis, a significant portion of the 800 000 in the final state of Kidney Disease.

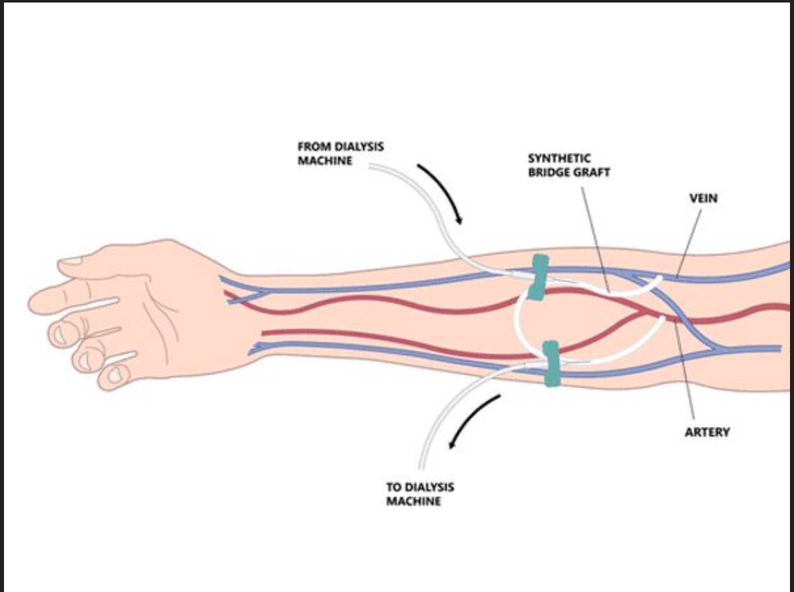


Kidney Dialysis, an Introduction



- **Why it's needed**
  - Kidneys can't filter blood, toxins and extra fluid build up.
- **How it works**
  - Blood pumped through an external filter machine
  - Fluid in Abdomen cleans blood.
- **AV Fistula**
  - Surgeon connects an artery directly to a vein in the arm to create a strong, long-lasting access point for needles.
- **Relatively High Rates of Failure**
  - 1-year survival rate for patients in Ontario is ~80%.
  - 5-year survival rates of about 40%, depending on patient age and general health.

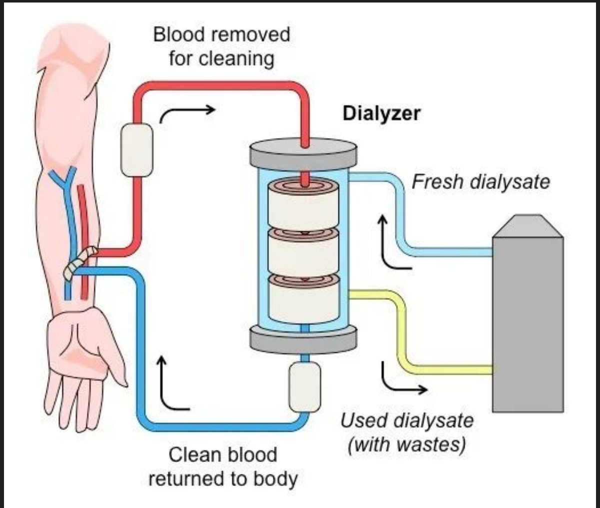
Fistula Requirements



- For an AV fistula to be usable for dialysis, it must undergo a maturation process. Maturation involves:
  - Vein Enlargement
  - Wall Thickening
  - Accessibility
- Failures in Fistula Maturation is caused by:
  - Stenosis (Narrowing of Blood Vessel)
  - Thrombosis (Blood clot blockage)

Current Innovations in the Space…

- Medical diagnosis is very observational, but attempts to add more quantitative metrics have been underway.
- One of these initiatives is using Computational Fluid Dynamics (CFD) to predict key parameters such as Wall Shear Stress.
    - In a procedure where AV Fistulas are created for Kidney Dialysis, 70% of fistulas failed to mature after a year (thicken appropriately in relation to the rest of the surrounding arteries).
    - After the addition of CFD metrics, this failure rate dropped to 10-20%!

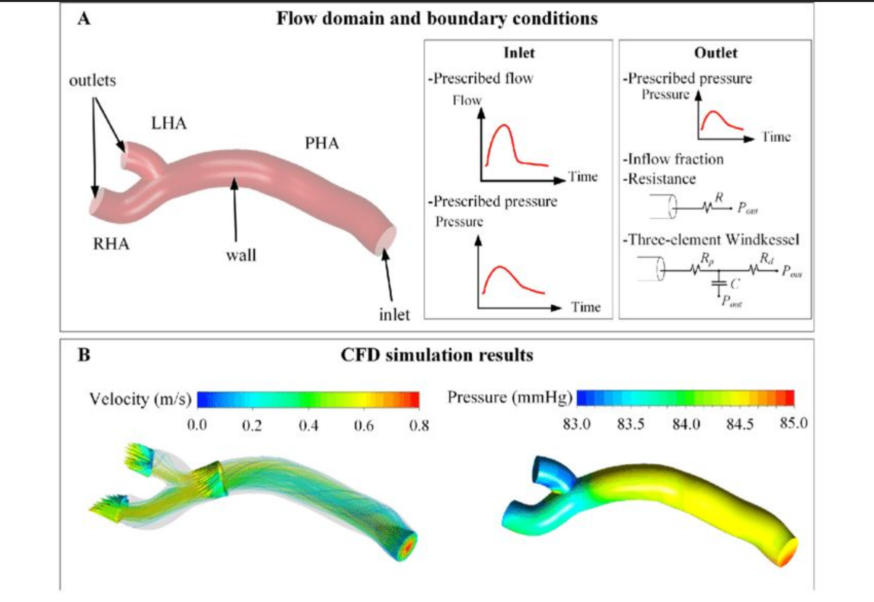


https://radielhealth.notion.site/from-barbarism-to-digital-twins

What is CFD?

Computational Fluid Dynamics & Dialysis

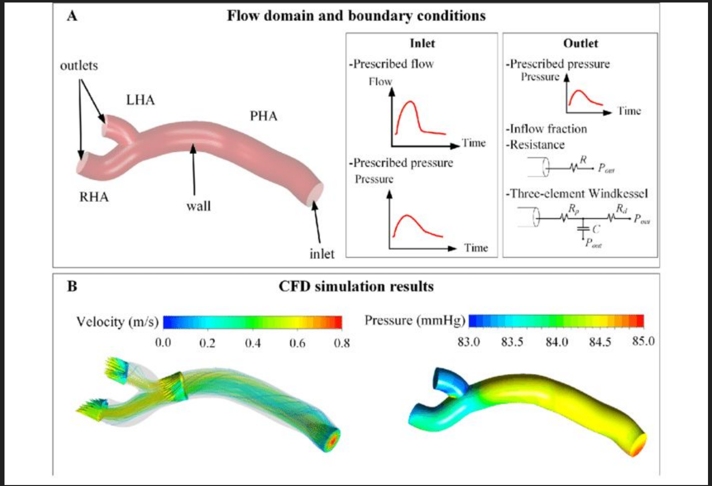
- **What is CFD?**
  - Computer simulations of how fluids (blood) flow through devices and vessels.
- **Spotting Problem Areas**
  - Identifies zones of low flow or high stress that can lead to clotting or vessel damage.
- **Design Optimization**
  - Adjusts shapes of access points or filter channels to achieve smoother, more even blood flow .
- **Patient Benefit**
  - Studies have shown better flow reduces complications, prolongs access lifespan, and supports improved survival rates.



Owen DG, de Oliveira DC, Qian S, Green NC, Shepherd DET, Espino DM. Impact of side-hole geometry on the performance of hemodialysis catheter tips: A computational fluid dynamics assessment. PLoS ONE. 2020 Aug 7;15(8):e0236946. doi:10.1371/journal.pone.0236946

Limitations of CFD and Our Role

- **Specialized Expertise Required**
  - Setting up and interpreting simulations requires trained engineers and clinicians.
- **High Compute Time and Cost**
  - Patient-specific runs can take ~6 hours and ~$2 000 per case



- Our solution addresses limitations of traditional CFD.
- Our first focus is on improving patient outcomes in dialysis.
- Machine learning predicts key flow parameters rapidly.
- This technology lowers costs and resource burdens.

Project Abstract

Project Abstract

Can a machine-learning surrogate, trained on high-fidelity CFD outputs from patient CT scans or ultrasounds, predict key flow parameters (pressure, velocity, shear stress) in seconds with accuracy comparable to traditional CFD simulations?

Why This Matters:

- ***Enables Real-Time Clinical Decision Making***
- ***Improves Patient Outcomes***
- ***Lowers Cost & Resource Burden***

Partners

- Dr. Sean Peterson → MME Faculty at UWaterloo and running the UW Fluid Flow Physics group, mentoring us in the development of models.
- Dr. Aaron Fenster → Medical Physicist from UWO, specializes in Vascular Imaging and Image Guidance. He is one of the inventors of 3D Ultrasound!

Proposed Solution

Full User Pipeline

1

Clinician starts off with a series of patient ultrasounds or CT scans

2

Platform turns those images to a 3D Mesh

3

Model is run and prediction of hemodynamic values on new mesh is outputted.

4

Those values are then used by clinicians to better inform their decisions

Progress Update

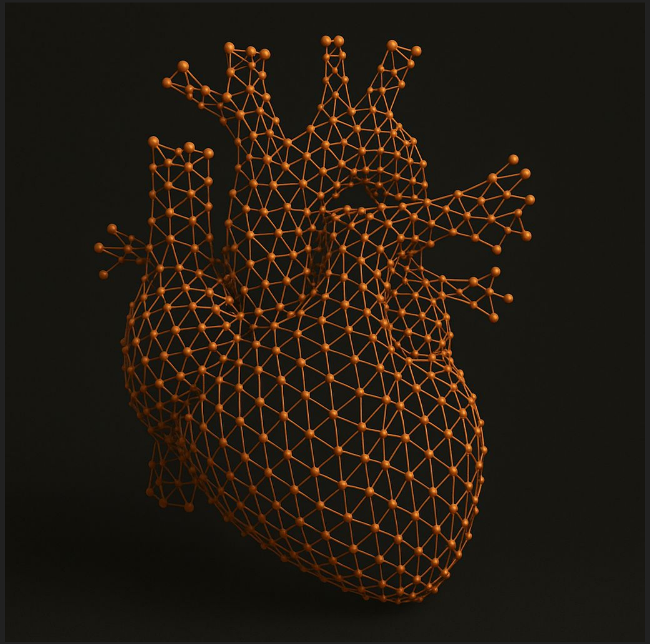
But first…

Lessons Learned from Last Time

- **Start small and focused.**
- **Big ideas are cool but implementable ideas get done**
- **Software must be built with** *scalability* **in mind, especially for a long-term project.**

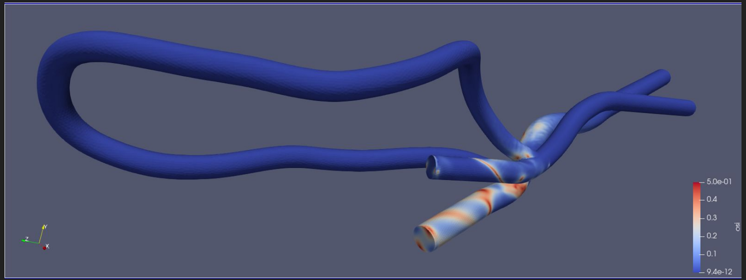
Reminder of our Start of Term Goals

1. Creating an accurate model simulation of a vascular artery (like an AV Fistula) with a neural network (PINN/GNN).
   - Prediction accuracy will be measured against performance of existing systems.
2. Generalize predictions on new unseen datasets.
3. Complete our user pipeline, integrating with Dr.Fenster's existing 3D ultrasound techniques.



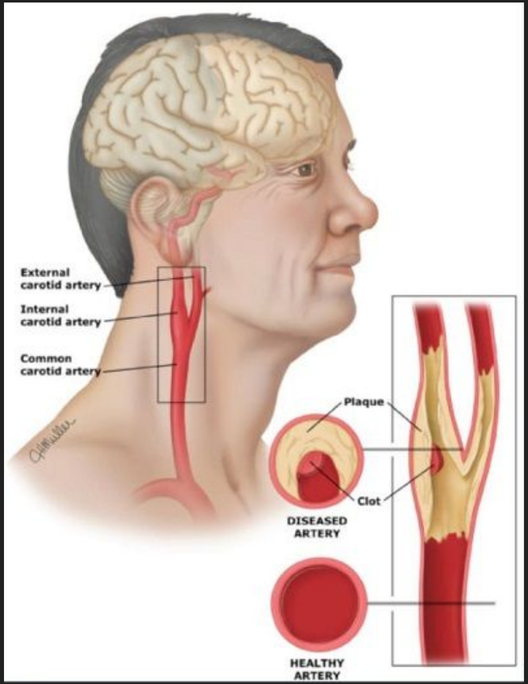
Goal One: Predict Accurate AV Fistula Metrics

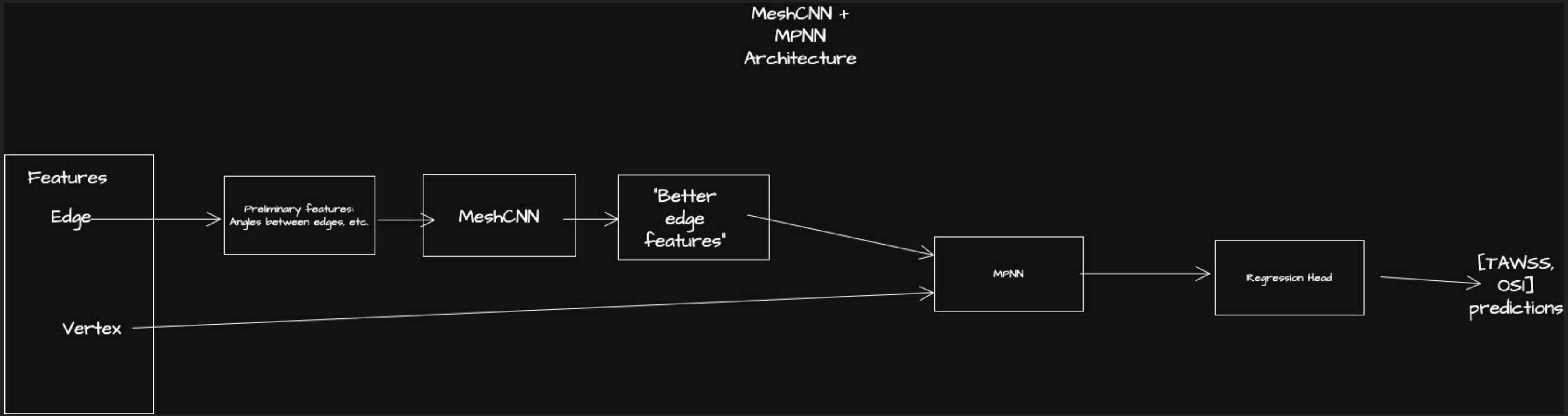
- **Initial Progress**
  - We initially began with a public dataset of 6 meshes.
  - No state-of-the-art (SOTA) for our machine learning models to compare against.
  - We only have CFD ground truth for comparison.
  - What is acceptable error?
    - We didn’t have an expert opinion
- **Resolution?**
  - Transition to carotid artery dataset from Prof. Aaron Fenster → generate proof of concept
  - Make use of Dr. Fenster’s expertise for what is clinically acceptable error
  - Create AV Fistula data after success with proof of concept success under supervision of Dr.Fenster’s lab.



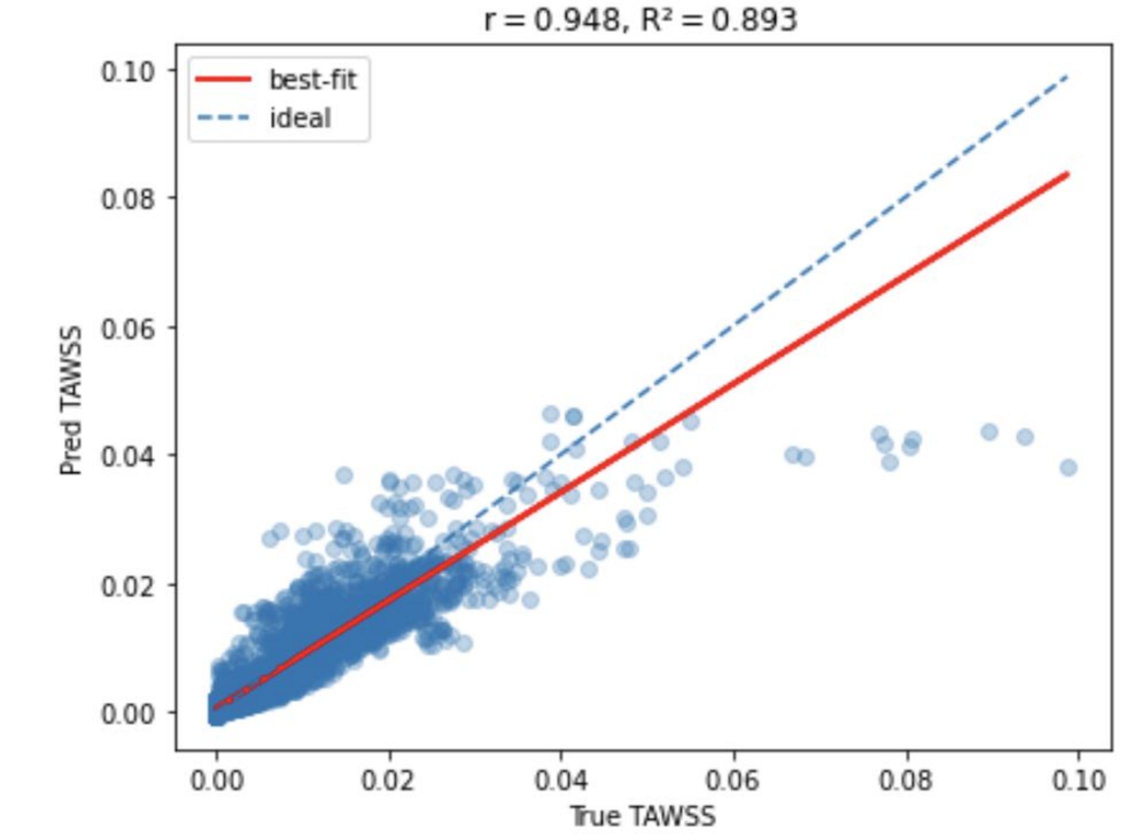
Carotid Artery Dataset

- Dr. Fenster's team at UWO has this dataset of 600 carotid arteries in 3D mesh form.
    - Idea was that having such a high amount of vascular meshes will be more than enough data for us to train a model.
    - *But wait? It's not the same artery from the AV Fistula procedure?* → Our main objective was to prove that it's possible to predict CFD metrics in vascular structures. This model will allow us to generate this proof of concept and a working architecture!
- UWaterloo approved our usage of this dataset!



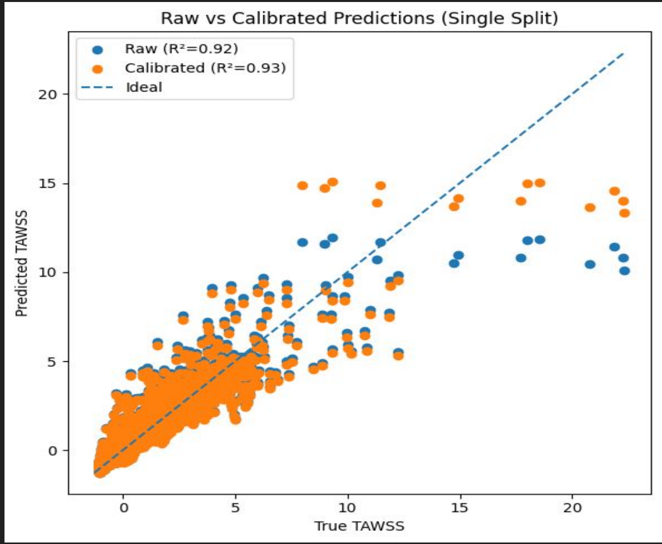

MeshCNN +
MPNN
Architecture
Features
Edge
Vertex
Preliminary features:
Angles between edges, etc.
MeshCNN
"Better
edge
features"
MPNN
Regression Head
[TAWSS,
OSI]
predictions

GNN + UNet + MPNN



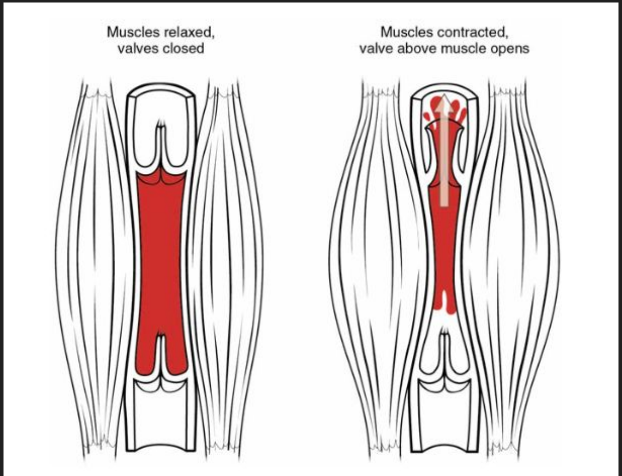
Goal Two: Ensure the model generalizes to new, unseen datasets

Proving good generalization for the model was difficult at first, due to our very small dataset…



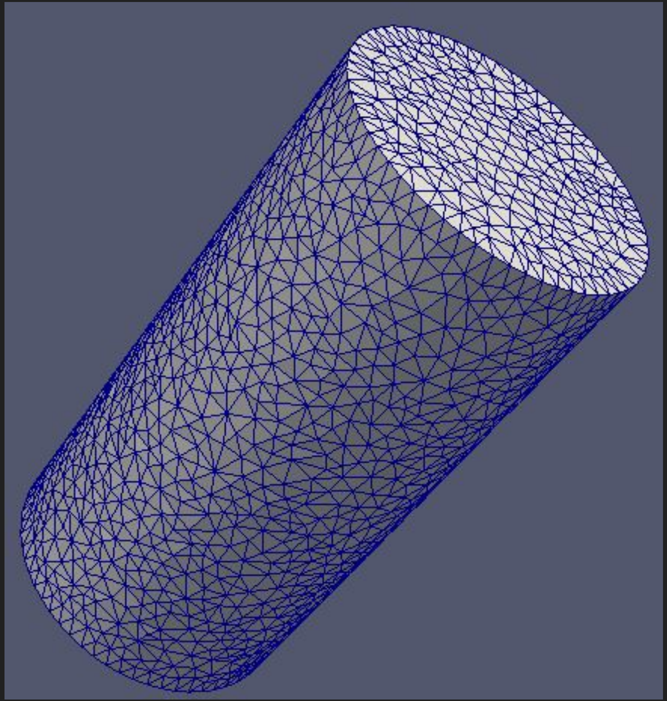
The hope was that moving to a larger dataset will allow us to create a model that can be easily adapted to different geometries.

Side Note: What are *Flow* (Fluid) Parameters?



- Fluid parameters describe how blood moves through vessels:
  - Pressure – force on vessel walls
  - Velocity – speed/direction of flow
  - Reynolds Number (a.k.a.“Flow Smoothness”), tells us whether flow is laminar or turbulent
- Inlet/Outlet Conditions
  - Define how blood enters and leaves the vessel segment being modeled
  - Vary with patient physiology (e.g., heart rate, blood pressure, viscosity)
  - Vary with geometry (different arteries, fistula vs. carotid, diameter, branching)
- **Why they matter: changes in conditions shift flow patterns and alter parameter values → one-size-fits-all models won’t generalize well**

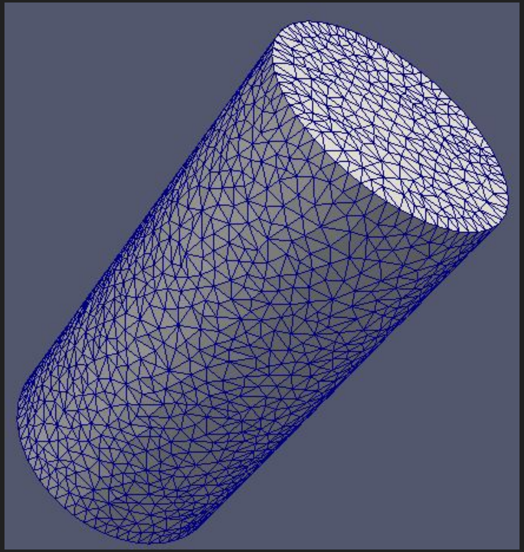
How Flow Parameters Impact CFD Output



Let’s take a simple cylinder!

How Flow Parameters Impact CFD Output

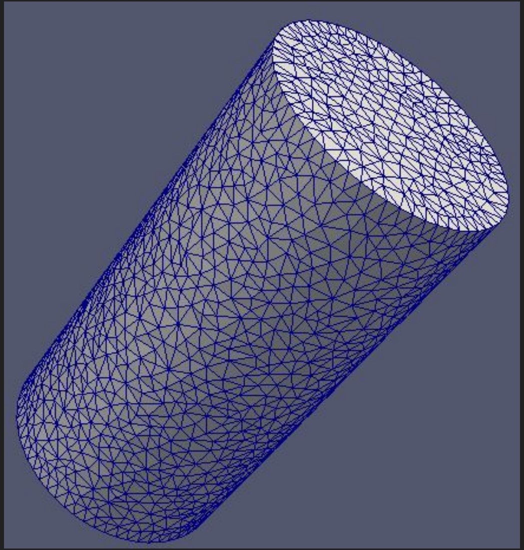
- Let’s take baseline Flow Parameters & Conditions:
  - Reynolds number: Re = ρUD/μ ≈ low (steady laminar)
  - Inlet: steady uniform velocity U, zero turbulence, Newtonian fluid
  - Outlet: fixed static pressure (e.g., $p$out = 0 gauge)
  - Wall: smooth, no roughness; no pulsatility
- And the resulting CFD Output will be:
  - Pressure (Cp) pattern: highest at the front where the flow hits, gently lower around the sides, small drop behind.
  - WSS: fairly even; mild peaks at the sides, lower behind the cylinder.
  - OSI: ~0 here (direction doesn’t flip because the flow is steady).



With calm, steady inflow, the stress and pressure patterns are predictable and symmetric!

How Flow Parameters Impact CFD Output

- What if we change our Parameters & Conditions?
  - Inlet: a bit “blunt,” with some pulse and small random wiggles (like a choppier river).
  - Outlet: lets the flow develop naturally (no strict pressure target), we’re at mercy of the natural forces of this flow
  - “Flow smoothness” knob (Reynolds number): turned up → the flow is more swirly and energetic.
  - Wall: still smooth.
- And the resulting CFD Output will be:
  - Pressure (Cp) pattern: a deeper low-pressure pocket behind the cylinder → bigger overall pressure drop (more drag).
  - WSS: drops in certain region where natural “trails” form (wakes) and hot spots move toward where the flow peels off and reattaches.
  - OSI: higher behind the cylinder, because flow direction there keeps changing over time.

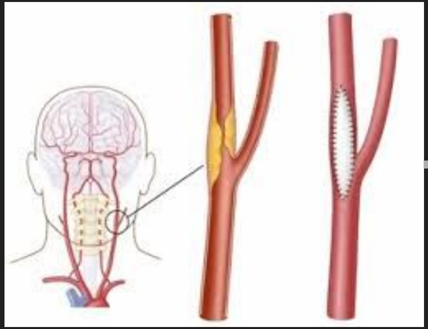


With a slightly different flow, our resulting CFD output is entirely different!

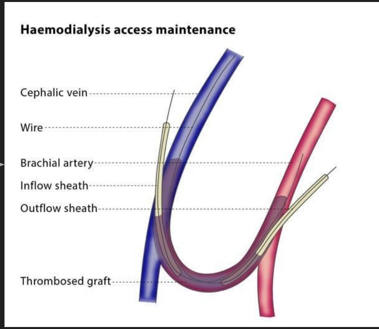
Limitations of Original Approach

We underestimated CFD this whole time, treating it as nothing more than a simple number to predict using ML.

- By jumping into a relatively complex 3D mesh (such as the carotid artery mesh) right away and trying to predict flow, we will run into several critical issues:
    - We're not sure how this can transfer to other vascular structures, even more so if they all have very different flow parameters and inlet/outlet conditions.
    - Each vascular structure we have from our dataset of carotid arteries are all a little different themselves, how can we be sure our flow parameters aren't changing drastically per geometry?



?



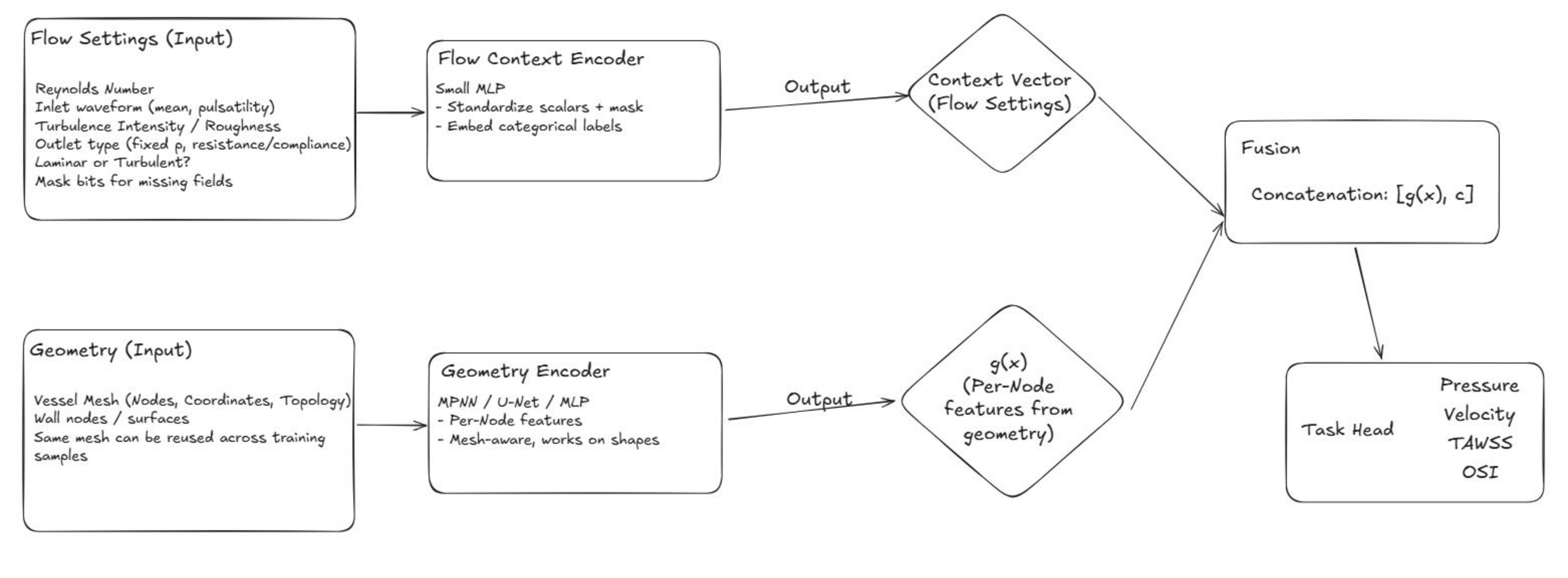
Limitations of Original Approach

Effectively, our original approach would leave us with a model that is trained on the geometries of 100s of carotid arteries without concern of the physics behind fluid flow (we assumed blood flow was constant all the time). This means our predictions weren't actually based in fluid dynamics and were very ***unscalable*** to other geometry types.

Is there a way to scale our approach better, where we take fluid flow into account for our predictions and we ***know*** *it'll work for varying flow parameters and for different geometry types?*

New Training Approach

Our network now learns a function of the flow settings!



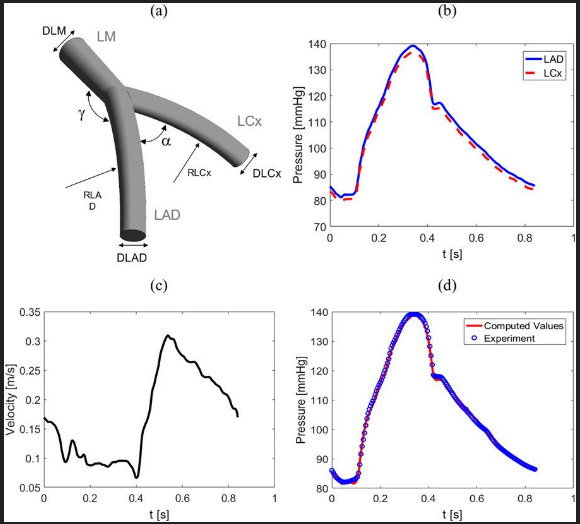
New Training Approach

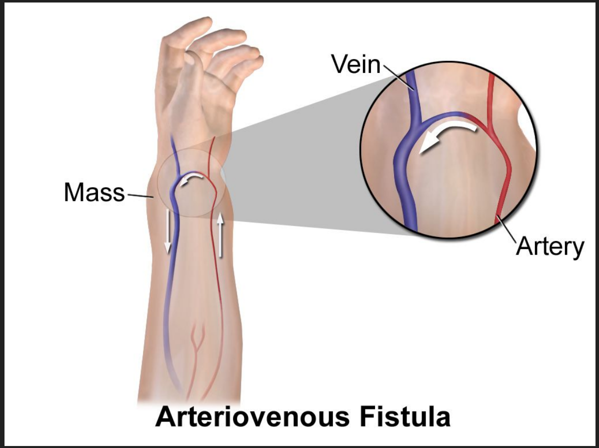
- Now, training the same vessel will yield different CFD outputs when the fluid parameters change, in accordance to the reality of physics.
- We are running these models on small, simple meshes to begin with, then ramping up complexity of meshes as we iterate the model itself.
    - This allows us to create a “suite” of smaller models that we know work for varying mesh types.

Goal is to take this smaller “suite” of models to help us build our main model for AV Fistulas more accurately.

Making Use of Model Predictions

- Key Metrics
  - Oscillatory Shear Index (OSI)
    - Quantifies directional changes in wall shear; higher OSI indicates disturbed flow
    - Time-Averaged Wall Shear Stress (TAWSS)
  - Time-Averaged Wall Shear Stress (TAWSS)
    - Measures mean shear stress magnitude; lower TAWSS suggests low-flow regions
- Quantify flow disturbance and shear magnitude to map vessel “openness”





Making Use of Model Predictions

- **Arterial “Openness”**
  - Combined OSI & TAWSS map where the vessel is well-perfused vs. prone to flow disruption
- **Risk Stratification**
  - High-OSI/low-TAWSS zones ⟶ ↑ risk of thrombosis (clot formation)
  - Persistent low-flow areas ⟶ ↑ risk of stenosis (vessel narrowing or closure)
- **Predicting Maturation Probability**
  - Use pre-operative OSI/TAWSS profiles to estimate access maturation likelihood
  - Quantify probability of successful fistula maturation based on regional hemodynamics
- **Surgical Site Selection**
  - Evaluate potential access locations
  - Recommend sites with the most favorable OSI/TAWSS signature
  - Minimizes predicted thrombosis and stenosis rates

Demo!

Fall Term Deliverables

- Continue to iterate on model, increasing complexity of 3D meshes with varying types of flow. General workflow is:
    - Create simple meshes with varying flow types, running CFD simulations to generate ground truth.
    - Run model on mesh with flow parameter arguments, testing error and iterating on model.
    - Goal is to have smaller ***suite*** of models each respectively adapted for various simple known CFD problems.
- Then in CS494 (Winter 2026), we will work with Dr.Peterson and our clinical partners to ensure the development of our model for AV Fistulas has equal amounts of geometric and physics based backing behind its predictions.

Our Team

- Project is being done in collaboration with Wat.ai, a student design team.
- Team split up into two:
  - CFD Team (working on running CFD simulations, and getting mesh from ultrasounds):
    - Ahash Ganeshamorthy (2nd year MD student)
    - Wallace Lee (4A BioMed Eng)
    - Naomi Estetu (2B BioMed Eng)
    - Jatin Metha (4A CS)
  - NN Team (working on developing NN for meshes):
    - Maximilian Popchapski (4A MathPhys)
    - Yana Jakhwal (2A STAT)
    - ***Rishabh Sharma (4A CS)***
    - ***Nicholas Jiang (4B CS)***
    - ***Sarvesh Sivakumar (4B CS)***

Questions?

Thank you for listening!

Site

Blog