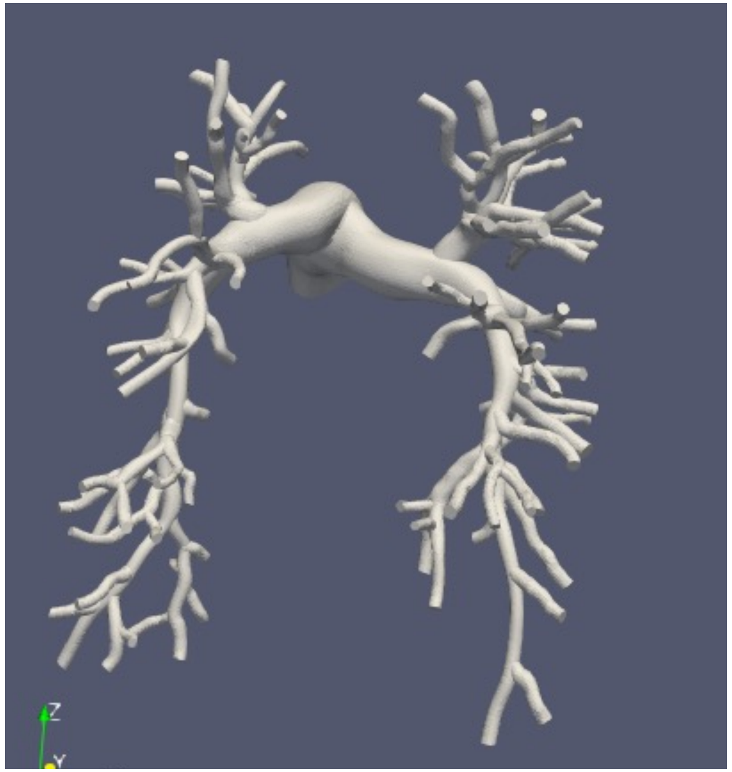
John Lee Summer Project

Probability Based Surgical planning tool for balloon angioplasty

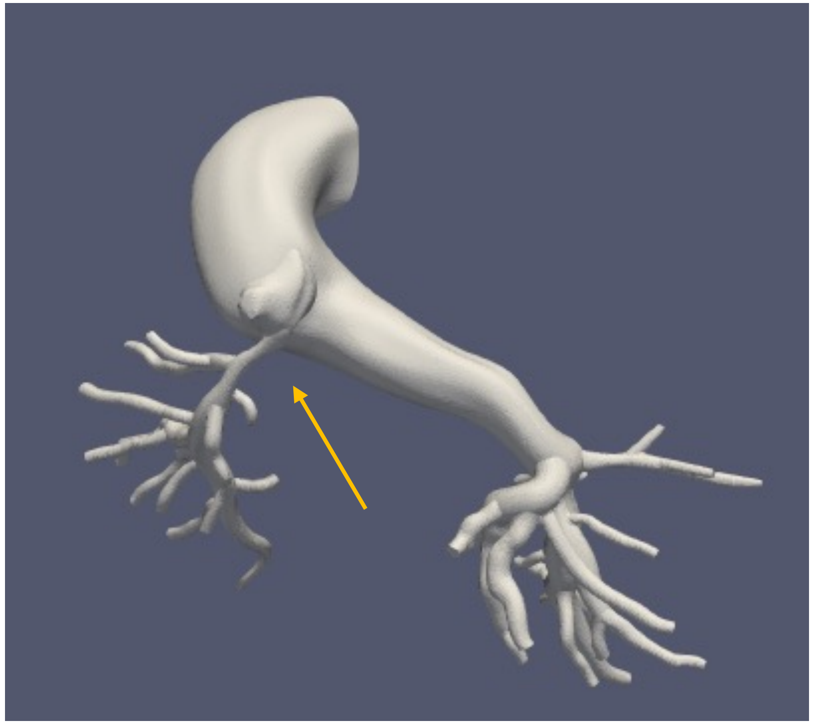
Data Gathering

Models

0080_0001 (Healthy)



0118_1000 (Alagille)



- Healthy Models
  - Artificially stenose models
  - Helpful to know actual healthy values for uncertainty quantification later
- Stenosis Models
  - Have actual stenosis which must be identified
  - Should have previously computed RCR boundary conditions

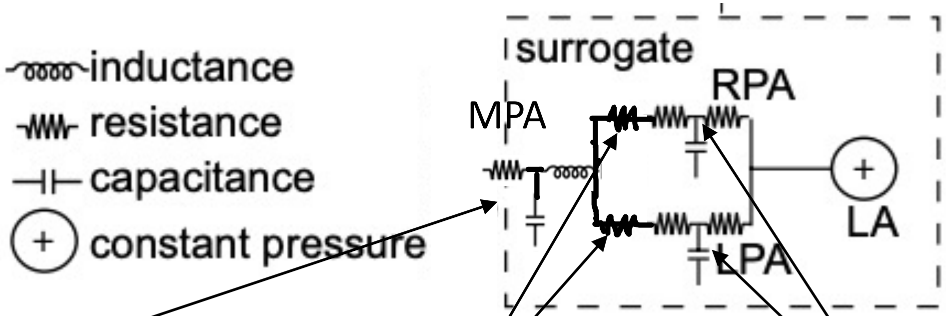
Issues with Models

- Some Models are not finely meshed enough to construct centerlines (Major issue, resolvable by reconstructing finer models)
  - '0005_1001', '0119_0001', '0081_0001', '0084_0001’]
  - SU0267, SU0269
- We will move ahead with 1 model from Healthy (0080_0001), and 2 Models from Stenosis (0118_1000, SU0238)

Healthy Models – BC tuning

Healthy Models/ BC tuning

Yang et. al. 2019 Surrogate model (Modified)



Constant RCL values for MPA

C is computing assuming linear eh_r of 1.2e6 dynes/cm^2

RPA Tree and LPA Tree precomputed resistances

Tunable RCR boundary conditions for LPA and RPA, with constant capillary wedge pressure of 7 mmHg

Optimization

- Ideal: obj func < .001 (.1% error)
  - Typically set lower and let it early stop.
- Early stop: patience (5 iter), patience_tolerance (1e-6)

Objective Function (4 error terms summed)

- Average Pulmonary Arterial Pressure (in mmHg)
  - PiecewiseLoss(12, 16, mPAP)
- Max (systolic) Pulmonary Arterial Pressure (in mmHg)
  - PiecewiseLoss(18, 25, maxPAP)
- Flow Split
  - Squared Error Loss(.55 * mean_inflow, Q_RPA)
- MSE vs flow
  - Cubic spline of Q_RPA_flow (f(x) using interp1d)
  - For n timesteps in inflow,

    $\frac{1}{n}\sum_{t=0}^{n} SquaredErrorLoss(.55 * inflow_t, Q_{RPA_t})$

*PiecewiseLoss(lower, upper, sim)

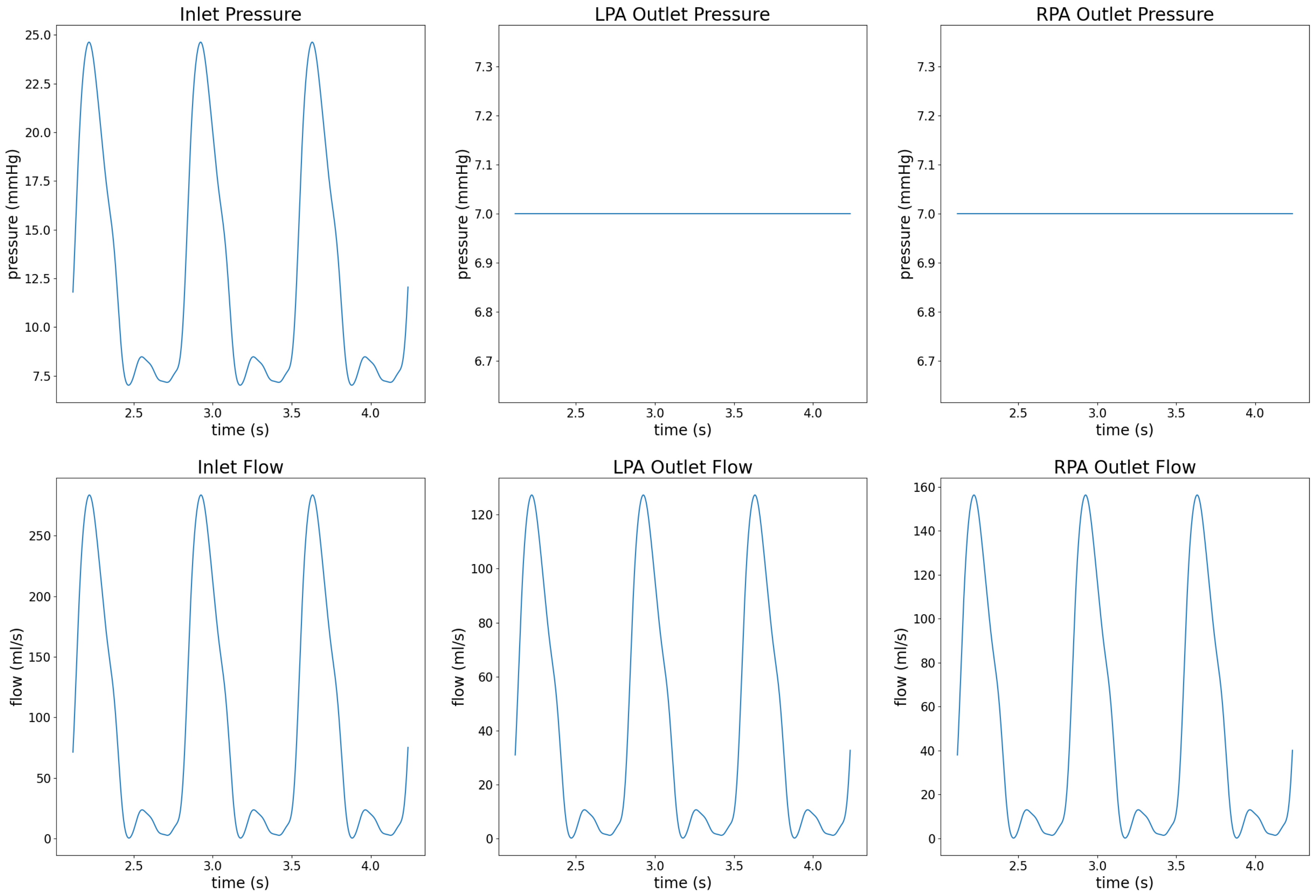
- If sim > upper : ((sim – upper)/upper)^2
- If sim < lower: ((sim – lower)/lower)^2
- Else: 0

- SquaredErrorLoss(target, sim)
  - ((sim – target) / target) ^2

Split RCRS (Yang et. al. 2019**)**

$$R_{p_i} = \frac{A}{A_i} R_p, \qquad C_i = \frac{A_i}{A} C, \qquad R_{d_i} = \frac{A}{A_i} R_d,$$

Optimization Results/Sanity Checks (ex. 0080_0001)




```
"Final Params": {
    "Rp_LPA": 40.53569025994334,
    "C_LPA": 5.236313079291195e-08,
    "Rd_LPA": 138.2928583999768,
    "Rp_RPA": 17.30900620609568,
    "C_RPA": 2.3083747766720217e-08,
    "Rd_RPA": 128.5561365891619
},
"columns": [
    "Optimized",
    "Desired"
],
"mPAP": [
    12.528713444748462,
    [
        12.0,
        16.0
    ]
],
"max_pressure": [
    24.629565106332247,
    [
        18.0,
        25.0
    ]
],
"rpa_flow_split": [
    0.5507125560747937,
    0.55
],
"Q_RPA": [
    49.128631153908934,
    49.0650645905741
],
"losses": {
    "mPAP_loss": 0,
    "Q_RPA_loss": 1.678466643720176e-06,
    "MSE_loss": 0.00021234343002127828,
    "maxPAP_loss": 0
```

Issues w/

- Lumped Multiple Objective optimization is slightly inaccurate (acceptable error)
- Capacitance of MPA is computed using a default EH_R value (not a significant influence)
- Resistance of RPA and LPA trees are a rough estimate from the automatic construction of the vessel tree
  - We do not know if the RPA and LPA resistances appropriately correspond to the pressure drop across the tree.
  - e.g. R_LPA = 5 cgs, R_RPA = 4 cgs -> ~.16 mPAP drop across the tree
- Should the Capillary Wedge pressure of 7 be the target after the BCs or after the tree itself?

Healthy Models - Artificial Stenosis

Methodology


```
"all_changed_vessels": [
    19,
    0,
    1,
    2,
    3
],
 "occlusions": [
     0.834324440125517,
     0.8653255373895141,
     0.7549403628015383,
     0.7549403628015383,
     0.7549403628015383
 ],
```

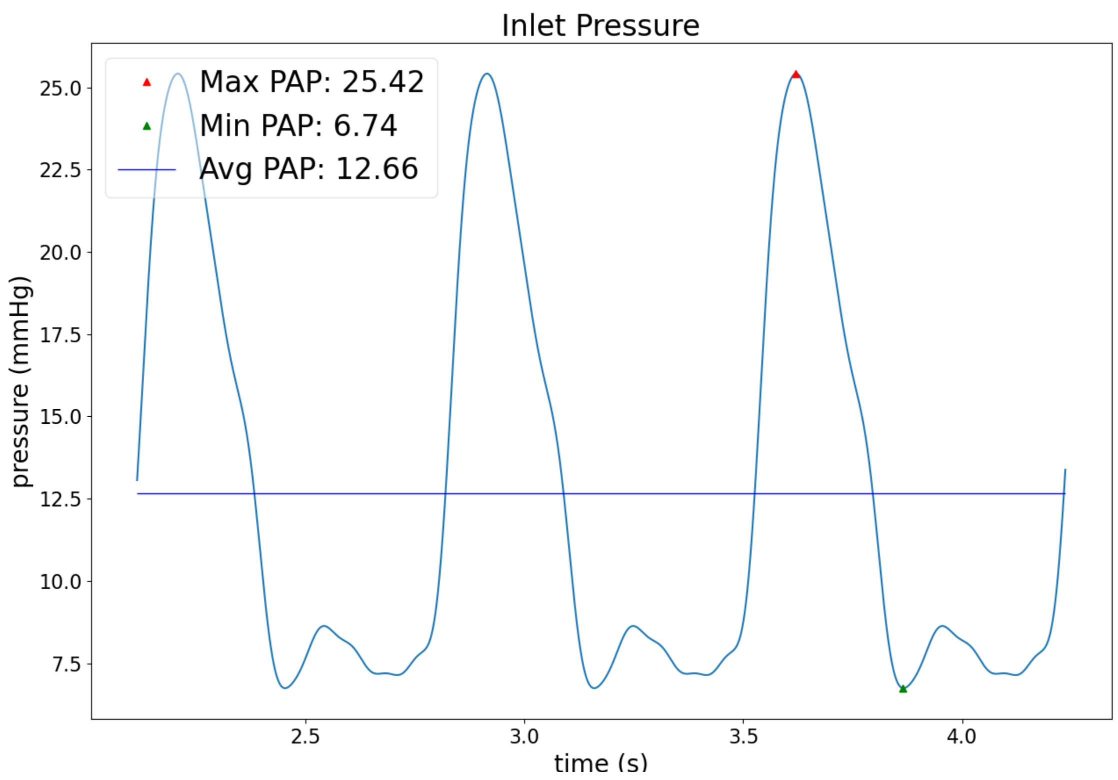

Sample Stenosis only stenoses MPA (0), LPA (1,2,3), RPA (19).

- Construct a Branch Tree of the PA w/ generations
  - Gen 0: MPA, Gen 1: RPA & LPA, …
- Using the Branch tree, determine **n** possible branches to stenose in the first **g** generations
- Use a **y** = *poisson*(λ = 2*g) to determine how many locations exactly to stenose (this is subject to change)
- Uniformly select **y** vessels from all **n** locations and give it an occlusion value from .75 - .9.
- Make changes to R, C, L corresponding to occlusion change in the

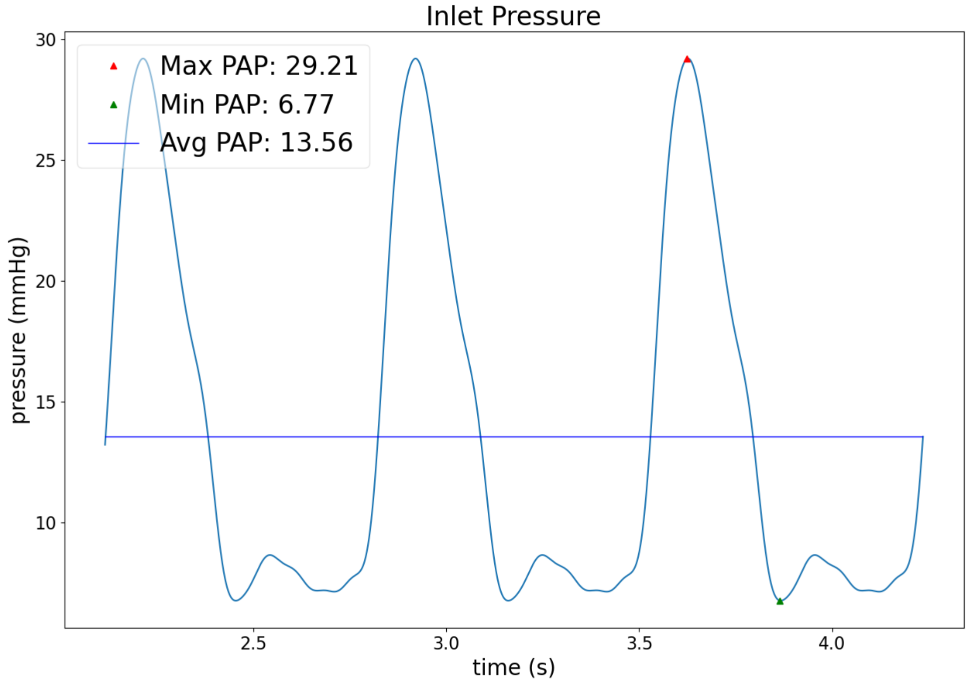
Healthy Models - Case Study 0080_0001

0D vs. 3D (Waveforms)

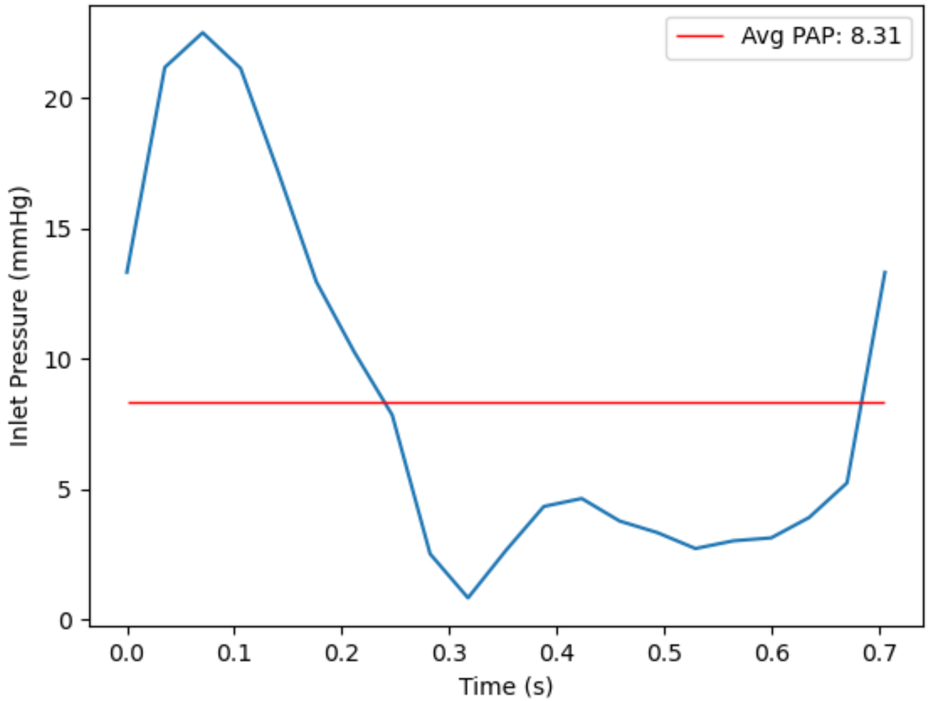
Base Solver



M1 Solver



3D Solver

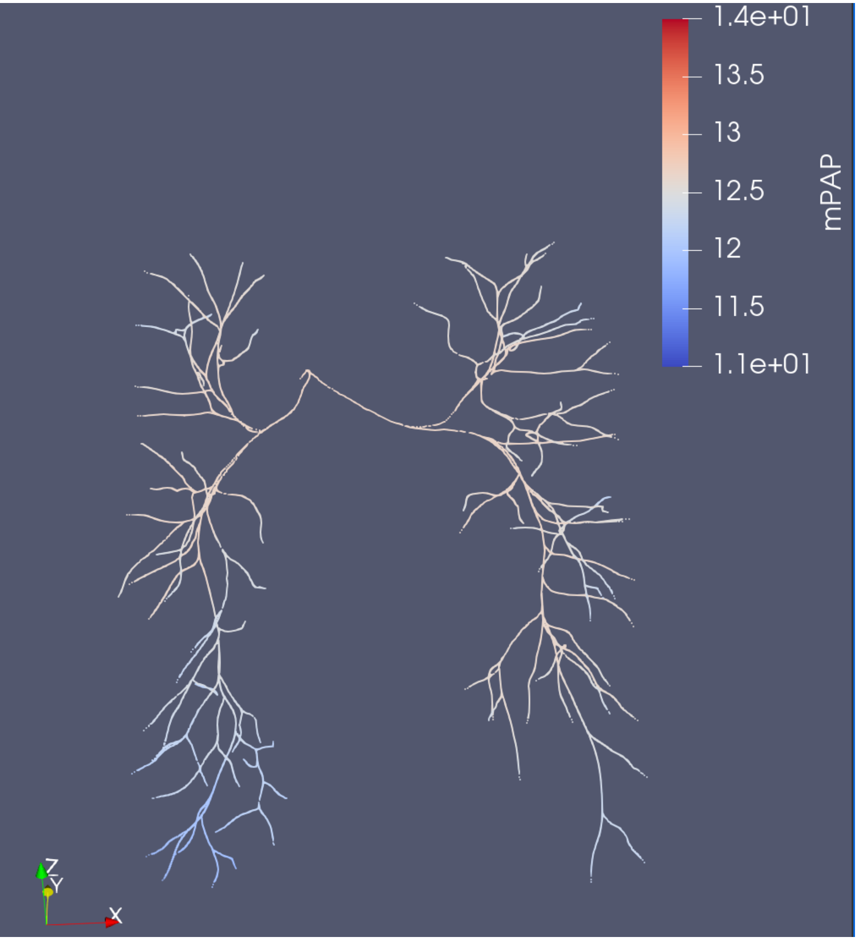


Notes:

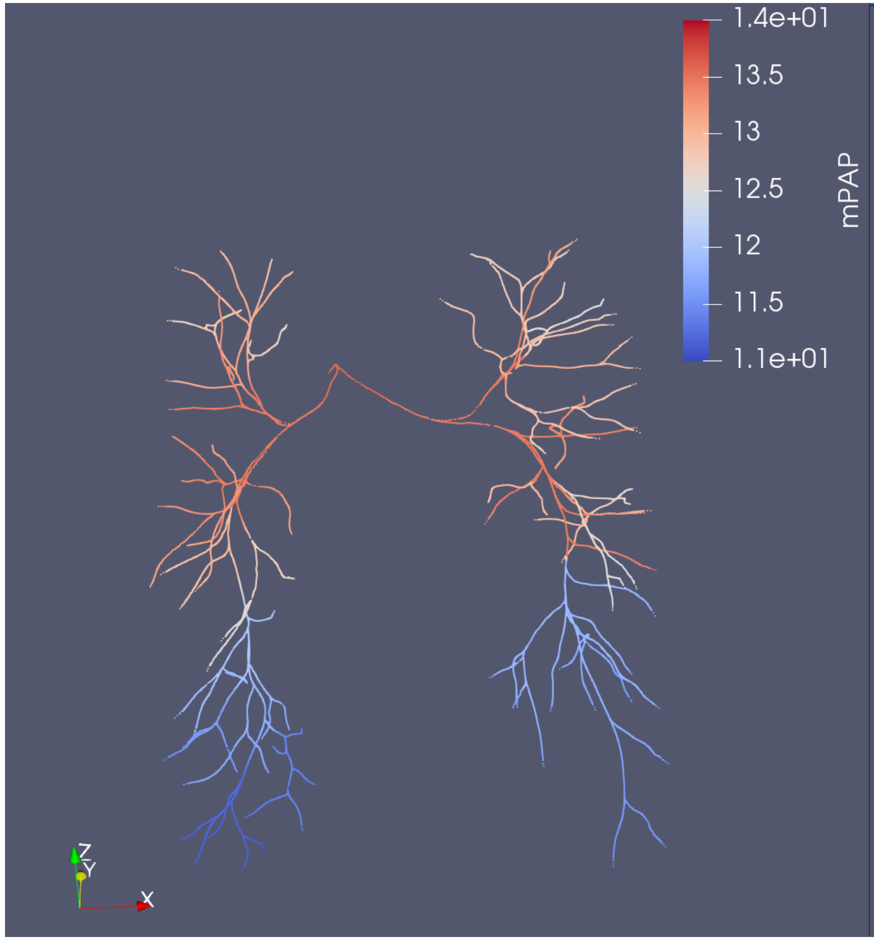
- mPAP drops to 1 in 3D solver?
- 3D solver uses different boundary conditions (does not consider rcr bcs)

0D vs. 3D (mPAP)

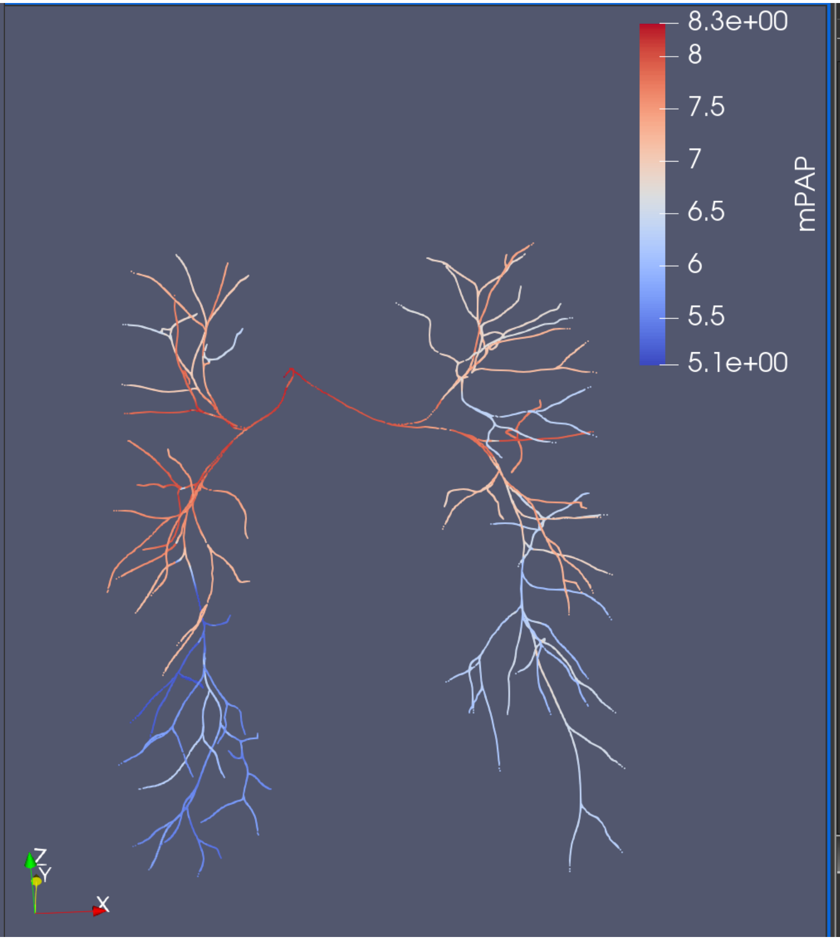
Base Solver



Method 1 (stenosis coeff)



3D



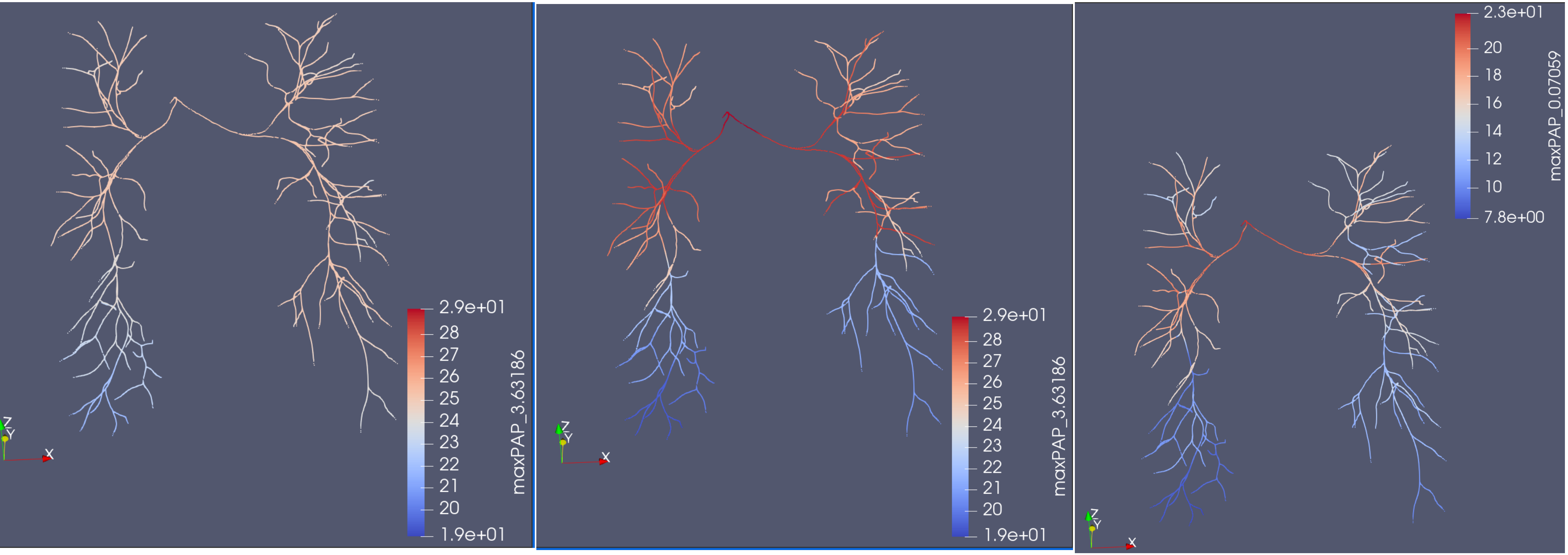
Notes:

- Larger pressure drop across tree w/ M1. Similar to the pressure drop in 3D.
- However, the 3D model seems a bit off/low. mPAP should be around 12 – 16, at least in inlet. May need to run own 3D

Not to scale

0D vs. 3D (maxPAP)

Base Solver | Method 1 (stenosis coeff) | 3D



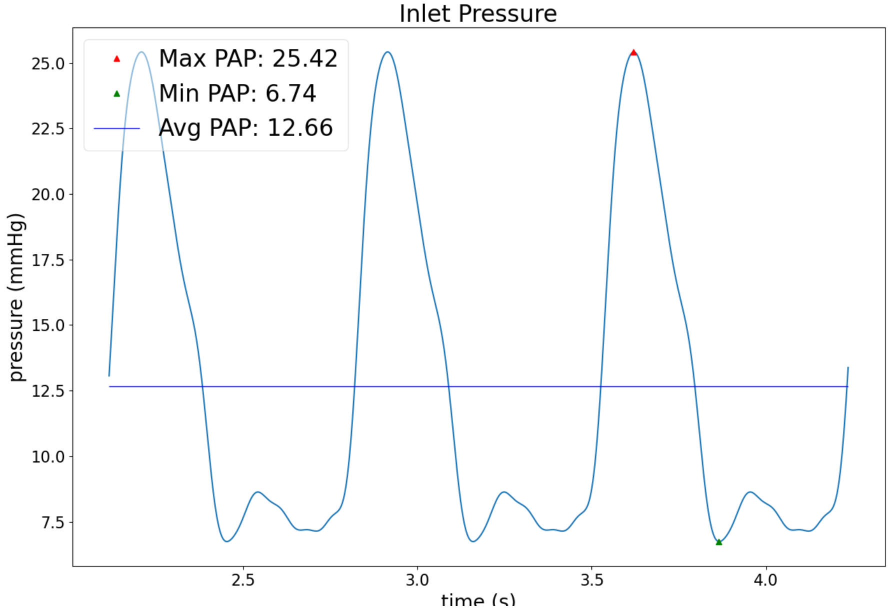
Not to scale

Notes:

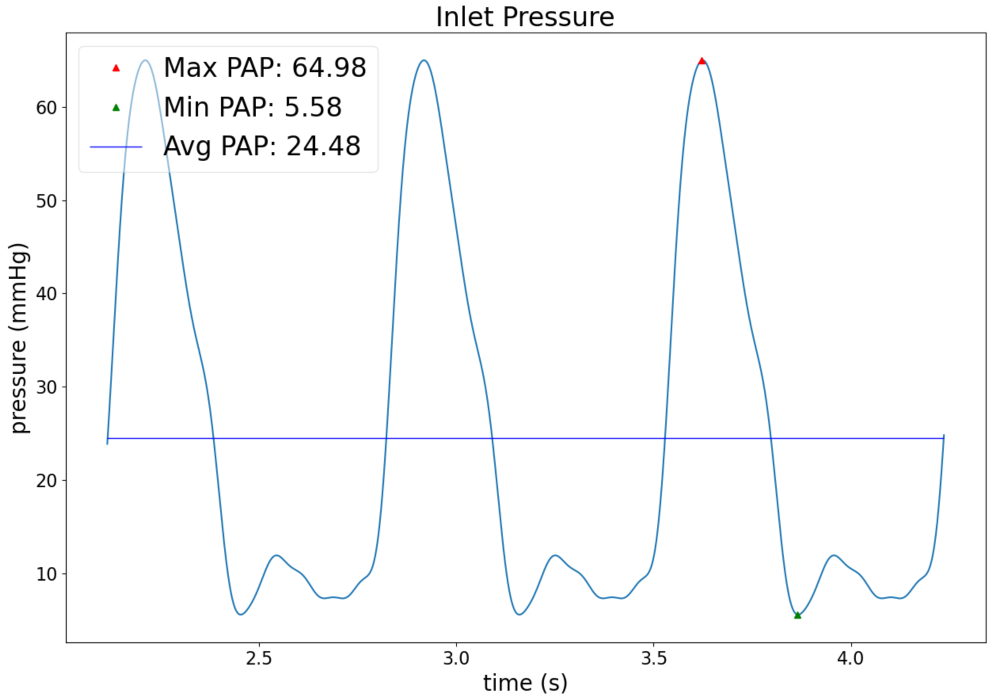
- Larger pressure drop across tree w/ M1. Less similar than mPAP, but still close.
- 3D model seems more reasonable here, with 23 mmHG down to 7.8.

Waveforms

Base, No Changes

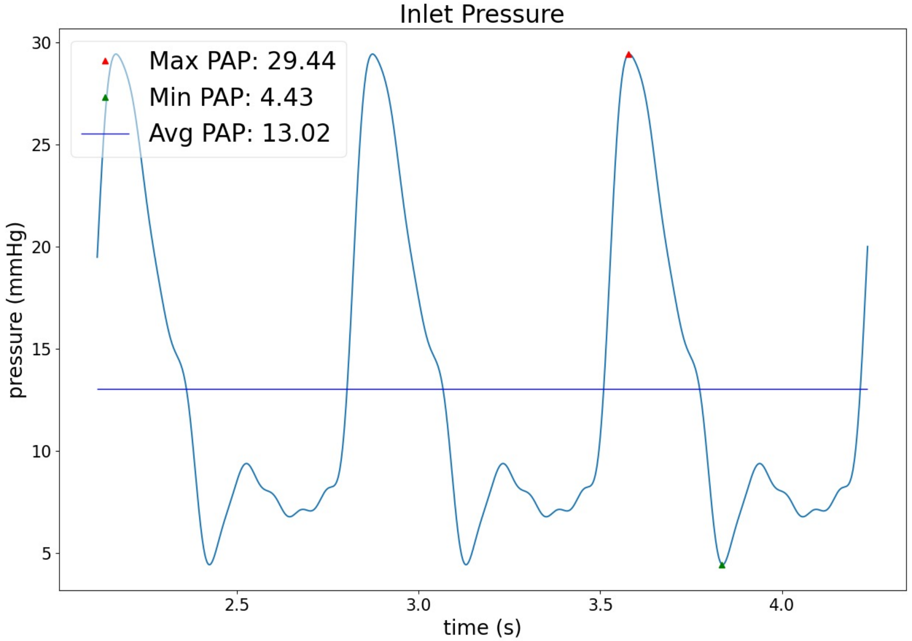


Random Stenosis (Left) (includes LPA)



108,	3,
130,	74,
131,	75,
132,	76,
121,	19,
73,	205,
28,	206,
8,	207,
1,	203,
2,	20

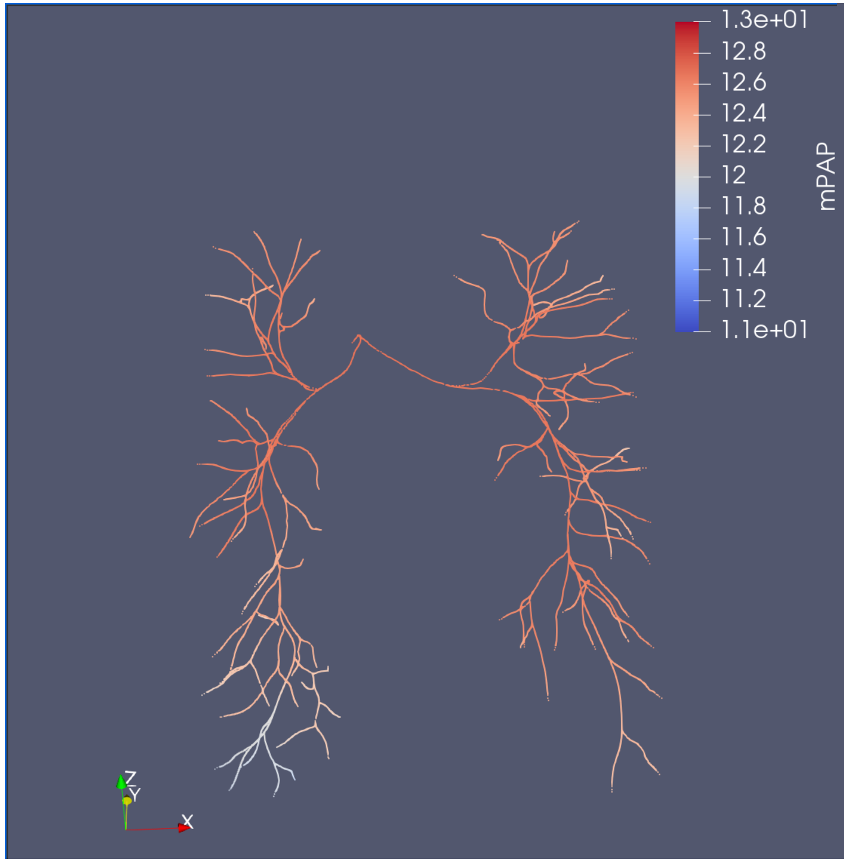
Proximal Stenosis (MPA, LPA, RPA)



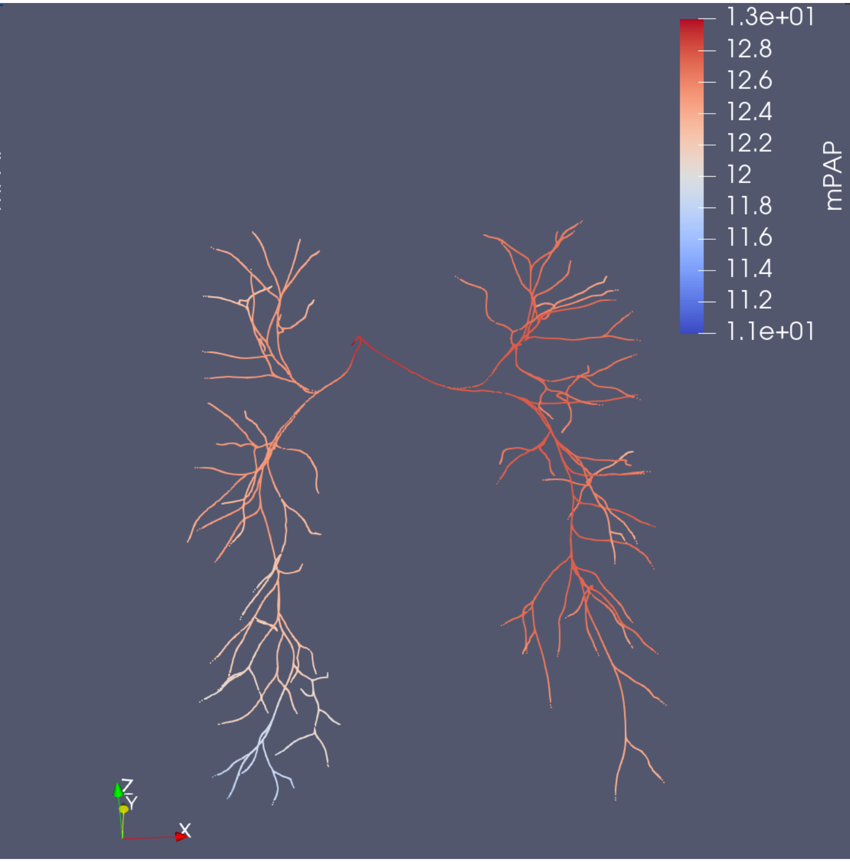
Notes:

- Stenosis is rather extreme/common to obtain that pressure increase
- Since Boundary conditions are tuned for healthy cases, they are not the most appropriate for the artificial stenosis
    - We can see that the min PAP is dropping
    - Do we need an Adaptive BC & how to do so
- Rather odd that stenosing the Proximal vessels are not drastically increasing pressure.

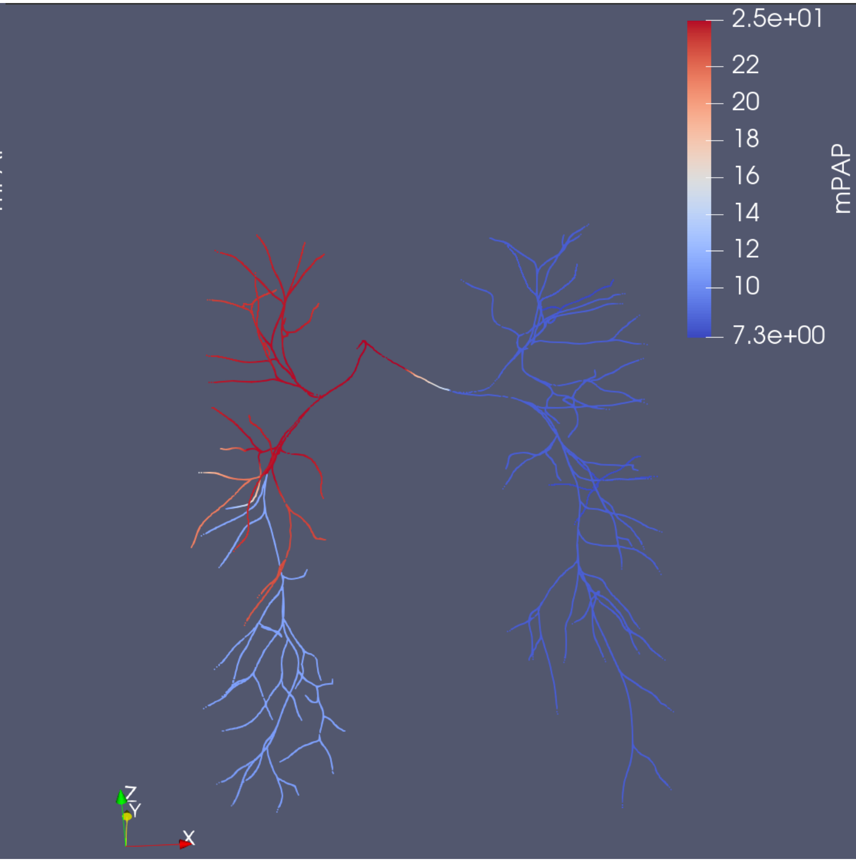
No Stenosis



Proximal Stenosis



Random Stenosis



Not same scale

Notes:

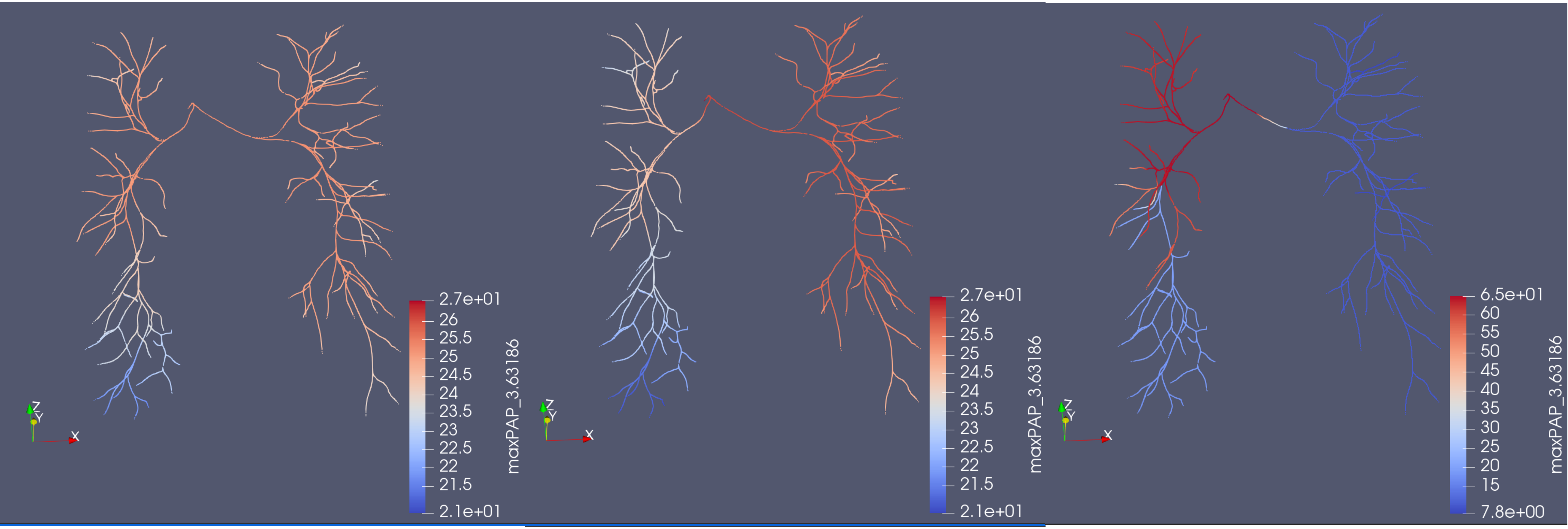
- Hardly any pressure drop w/ None & Proximal
- Significant Pressure Increase/Drop across tree with more stenosis Points.
- Positive indication that stenosis is at least working, but must test with less occlusion @ less points

mPAP

No Stenosis

Proximal Stenosis

Random Stenosis



Not same scale

Notes:

- Very similar to mPAP

max PAP

Next Steps w/ Healthy

- Check with less stenosis and occlusion
- Maybe consider a different way to select stenosis points
- Double check realism?
    - Run a 3D to compare
    - Run 3D of stenosis case (to look at in the future)

Stenosis Models – Stenosis Detection

Stenosis Models

- Only use models where an RCRT.dat file is provided for 3D simulations
    - Must be mapped back to 0D style where face/cap names are also included in the file
- Comes from both VMR & Ingrid’s previous models

Identifying Stenosis Methodology

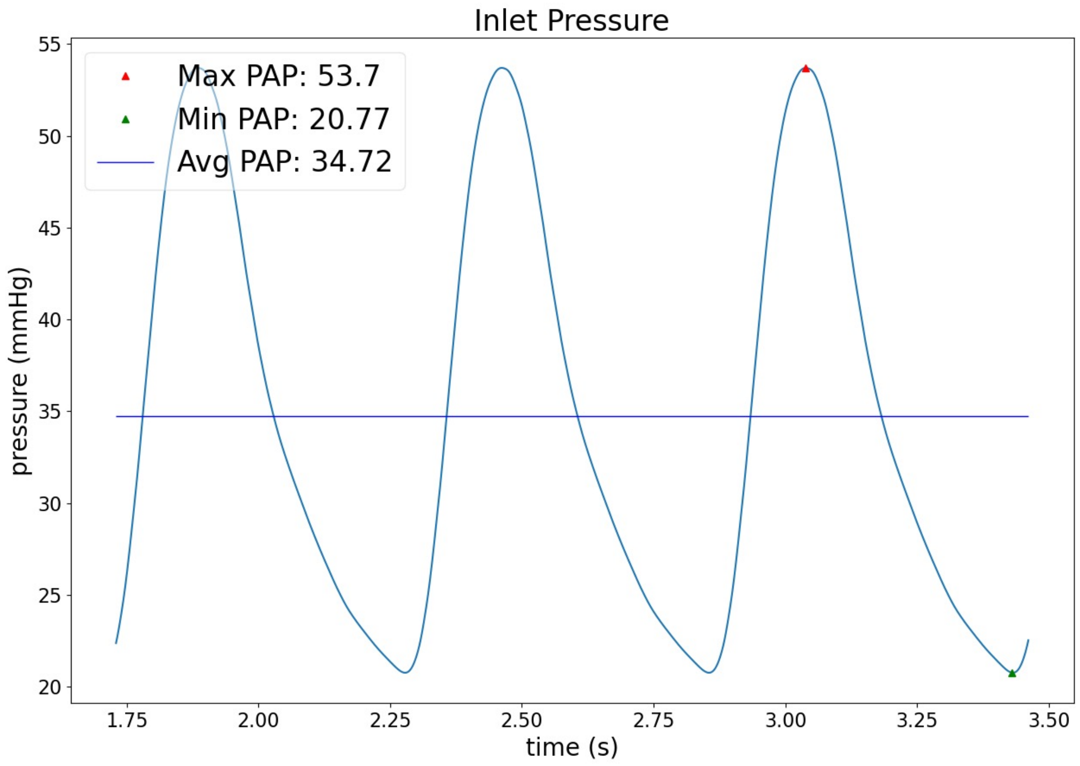
- Construct a Branch Tree
- Using $D = 0.001 + a * order * e^{(b * order)} * age^{c}$
  - a = 1.203e-4, b = 0.3927, c = 0.2381
  - We assume order is roughly 16 – generation, since gen 0 = MPA = order 16
  - https://journals.physiology.org/doi/full/10.1152/ajpheart.00123.2020
- For a branch, compute the control resistance for that length. If the actual resistance is > **r_threshold** * control resistance, then we consider it a stenosis point. If not, we iterate through segments in the branch and repeat for the individual vessel segment
- Alternative Proposal: Run a 0D simulation and observe the local effect where pressure drops > n%

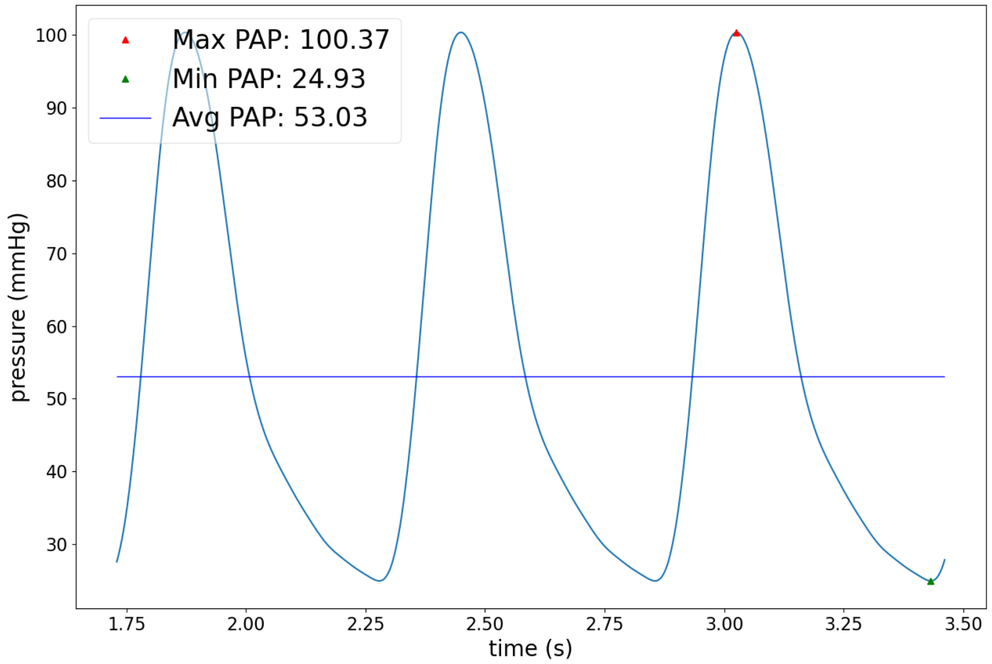

```
"r_threshold": 4,
"stenosis_vessel_ids": [
    1,
    7,
    10,
    32,
    33,
    34,
    42,
    43,
    44,
    23,
    27,
    28,
    29,
    38,
    49,
    62,
    67,
    69,
    70,
    9,
    36,
    37,
    59,
    60,
    68,
    8,
    47,
    48,
    31,
    54,
    63
],
"total_sten_length": 24.01498024898787,
"total_tree_len": 54.179403264197745
```

Stenosis Case Study Model - 0118_1000

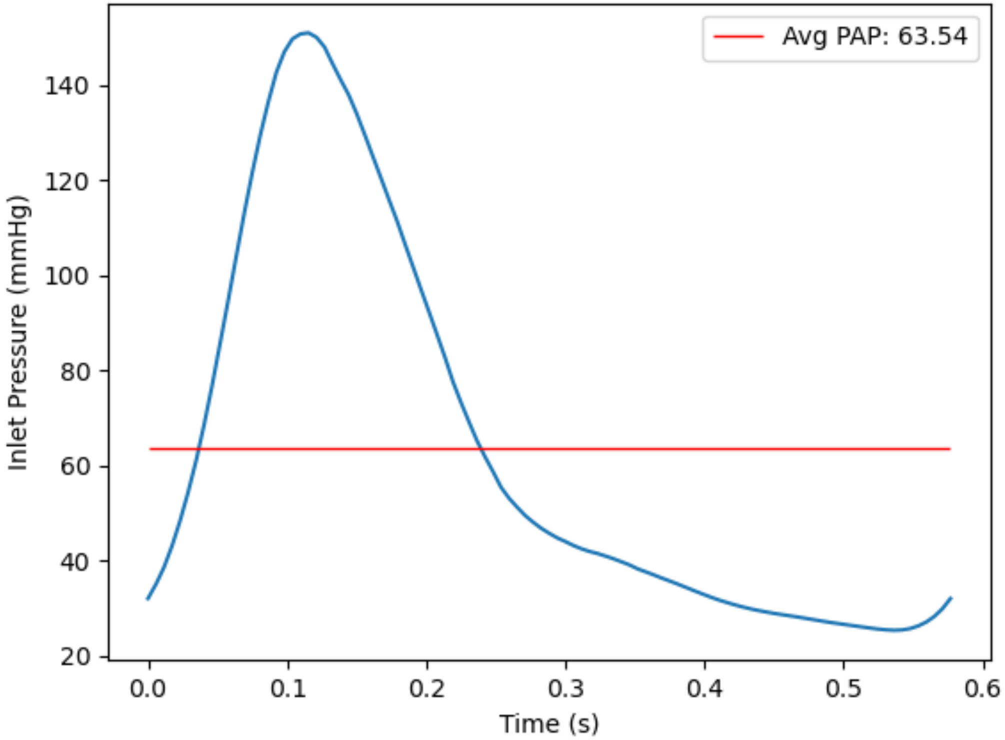
0D vs. 3D (Waveforms)

Base Solver





M1 Solver

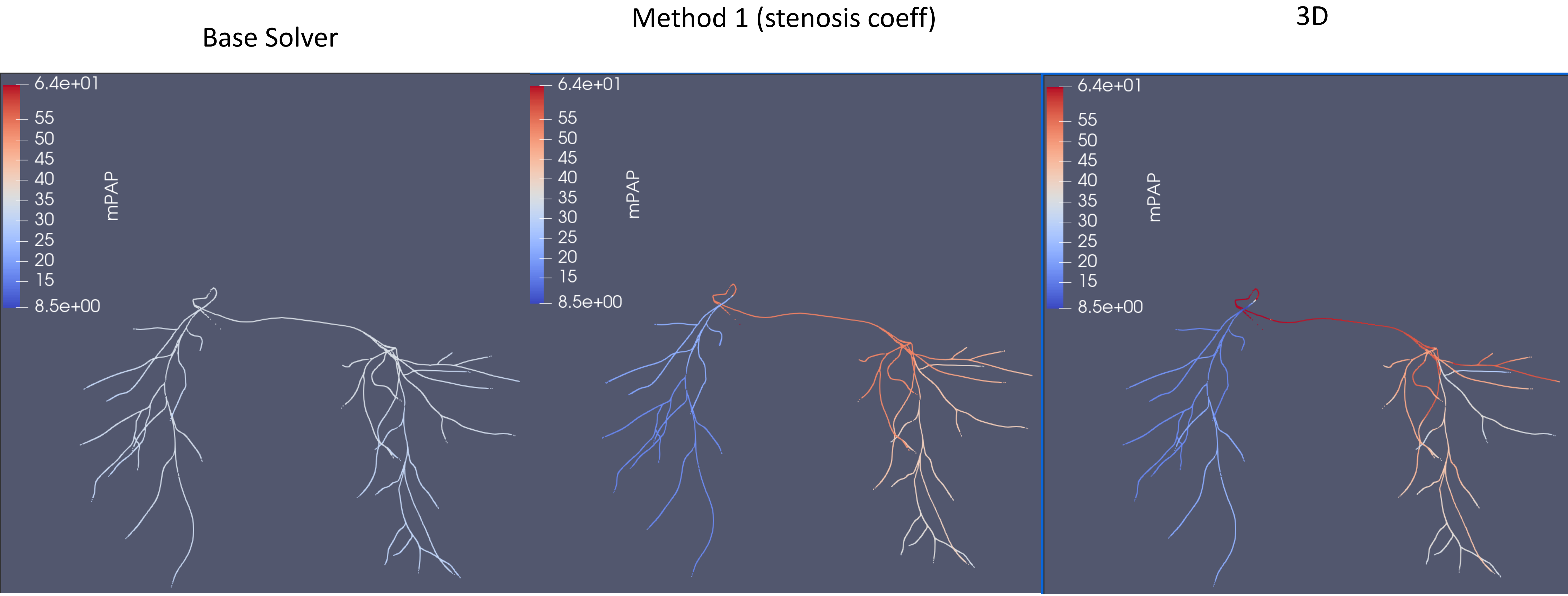


3D Solver

Notes:

- M1 seems to capture 3D better in general, but still a little low
- Waveforms seem kind of odd, do they need retuning?

0D vs. 3D (mPAP)

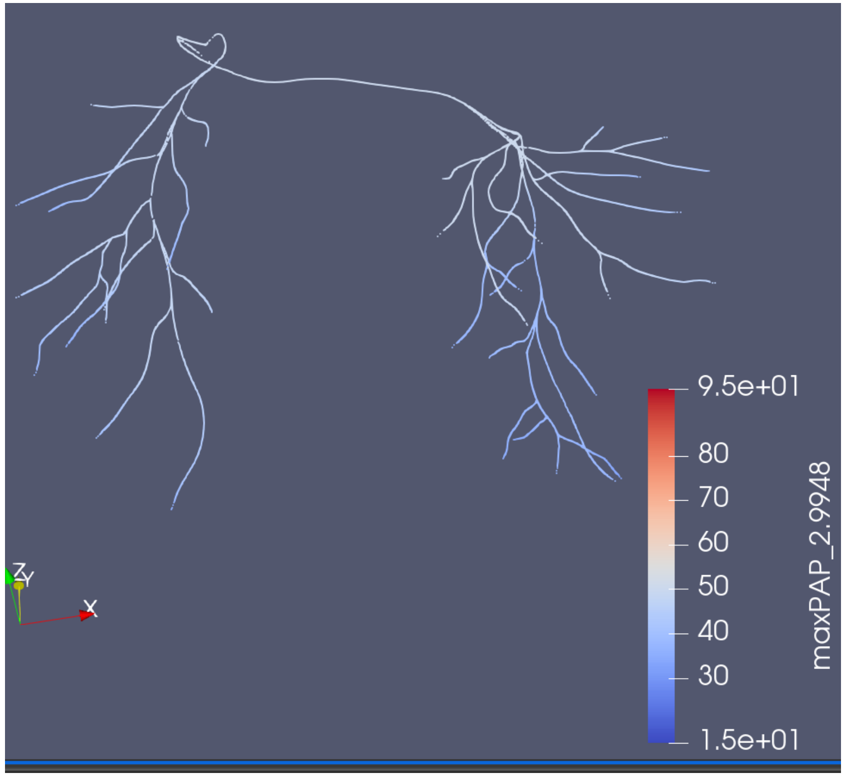


Notes:

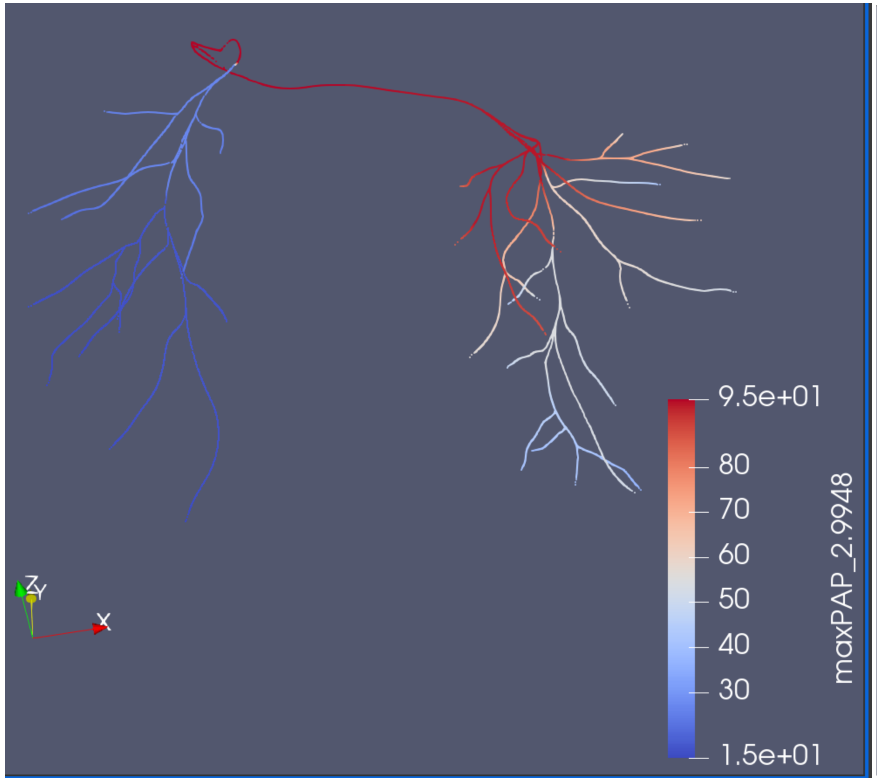
- Larger pressure drop across tree w/ M1. Definitely capturing flow/pressures drops better
- 0D Solver Bc's were taken exactly from 3D simulation, so the 3D should be an exact match

0D vs. 3D (maxPAP)

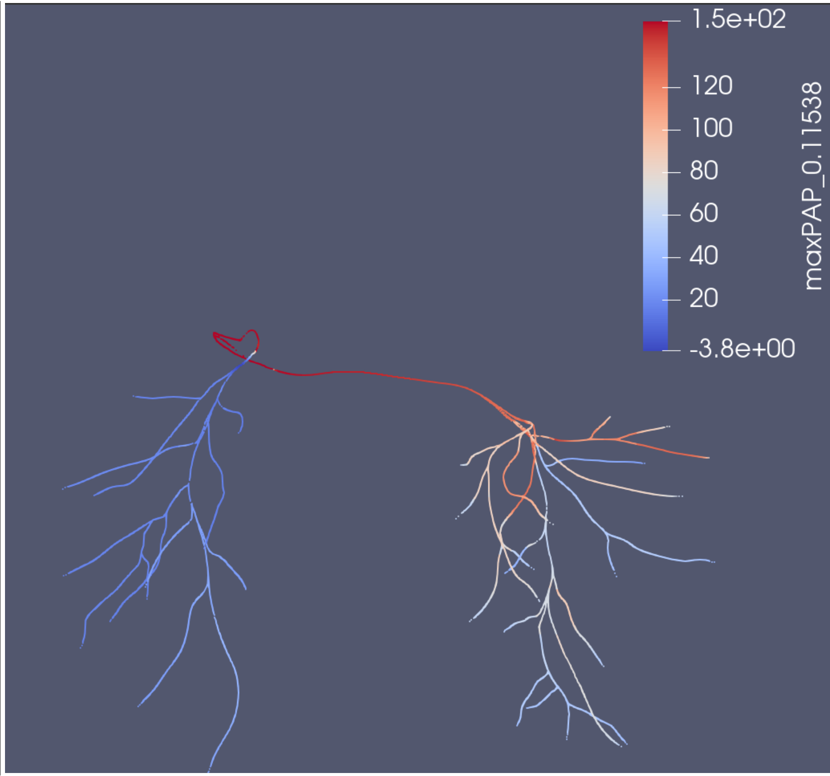
Base Solver



Method 1 (stenosis coeff)



3D



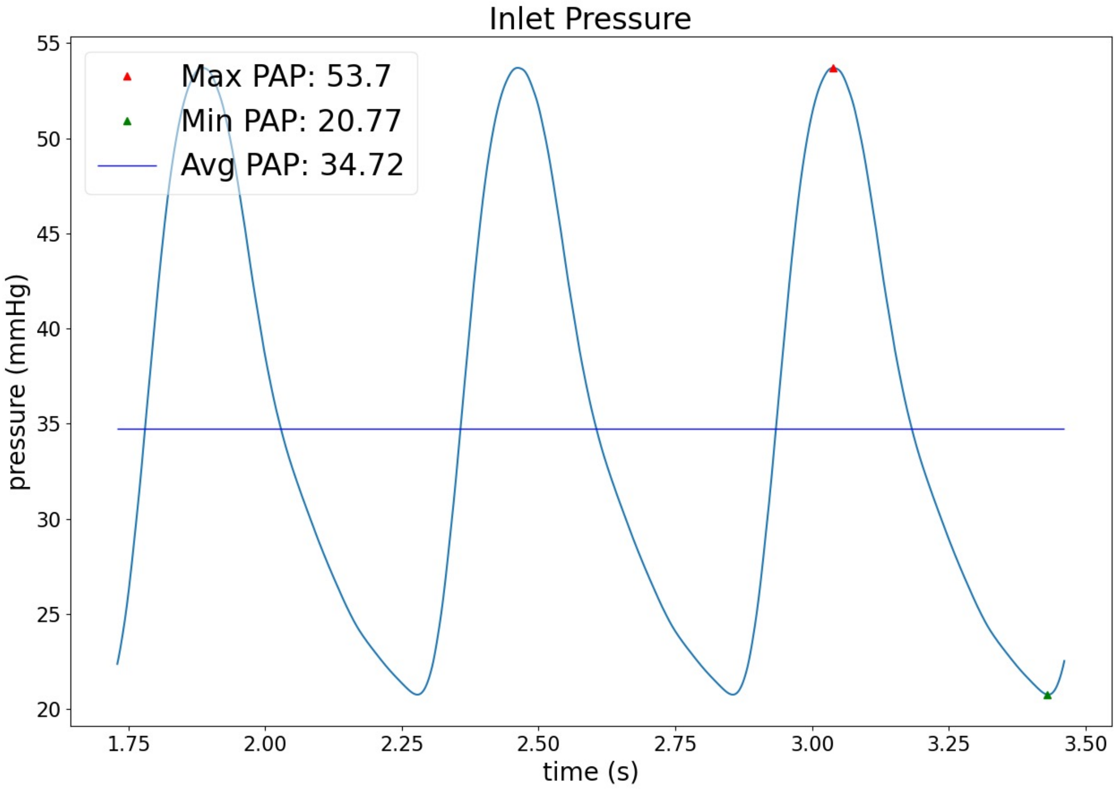
Not to scale

Notes:

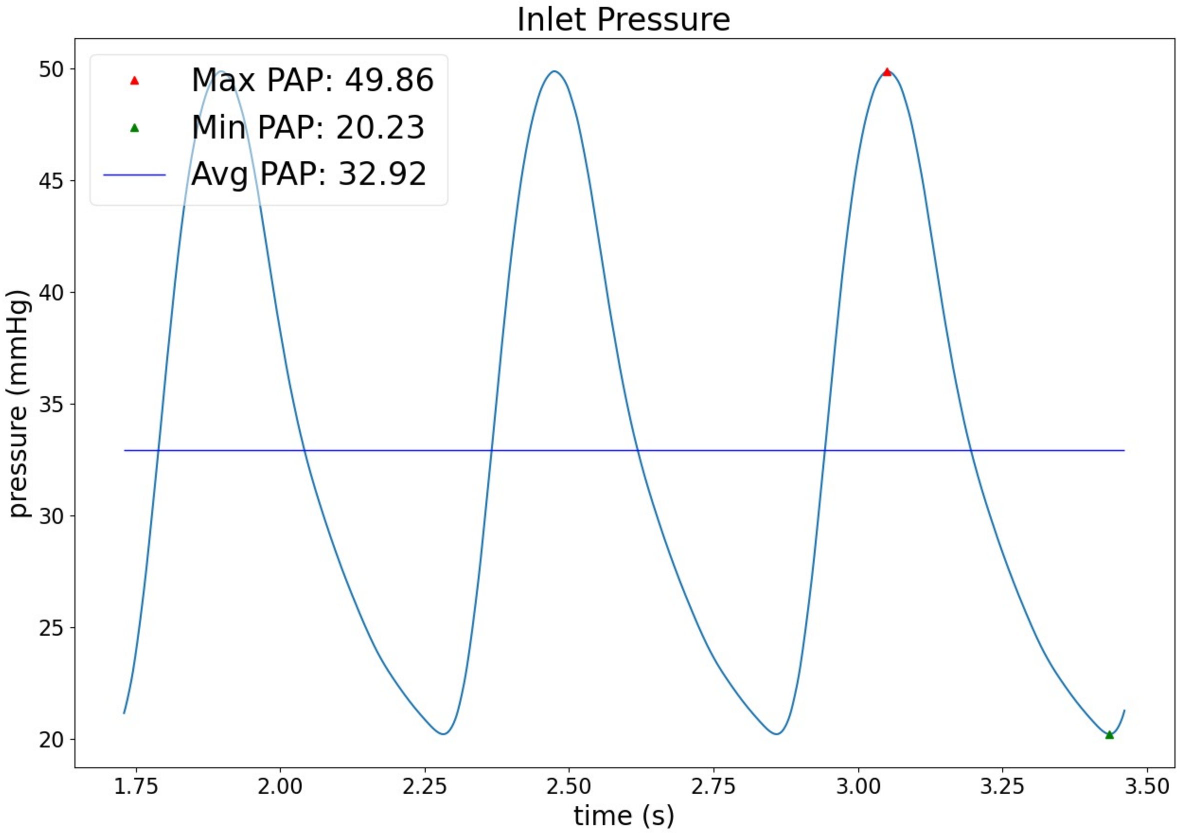
- There is definitely a larger pressure drop w/ M1
- 3D model has a negative pressure at choke point in RPA? Is this even valid
  - Ask in lab meeting

Original vs. Fixed (Waveforms)

Base Solver



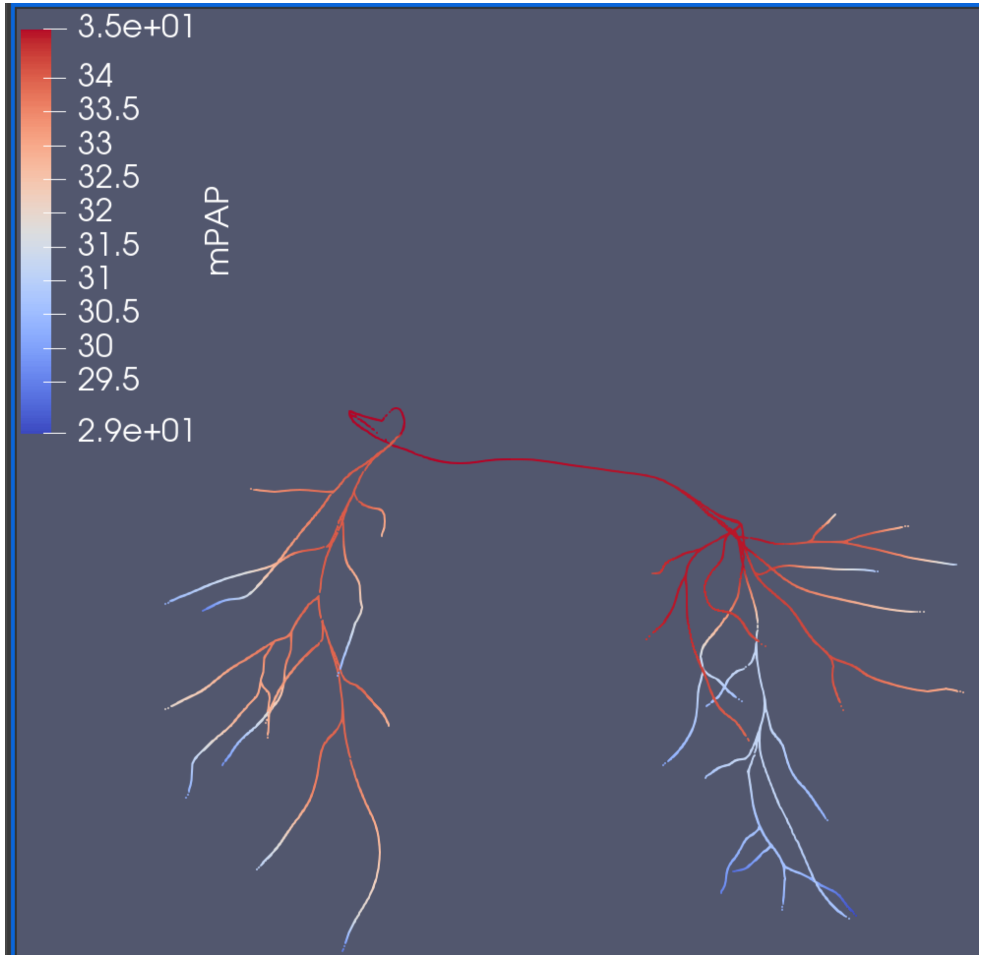
Fixed Solver



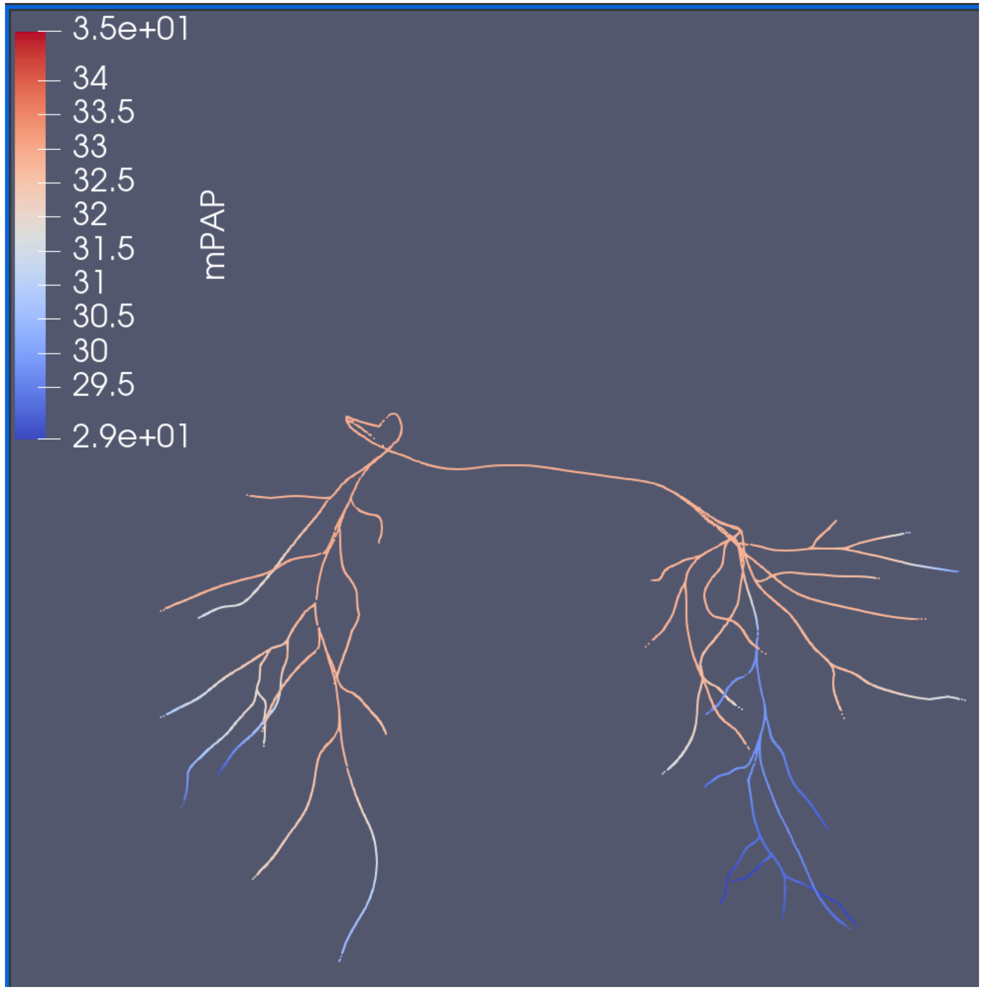
Notes:

- Only Minor Reductions, as expected since most of the stenosis was encountered in the junction

No Fix



Fixed Stenosis

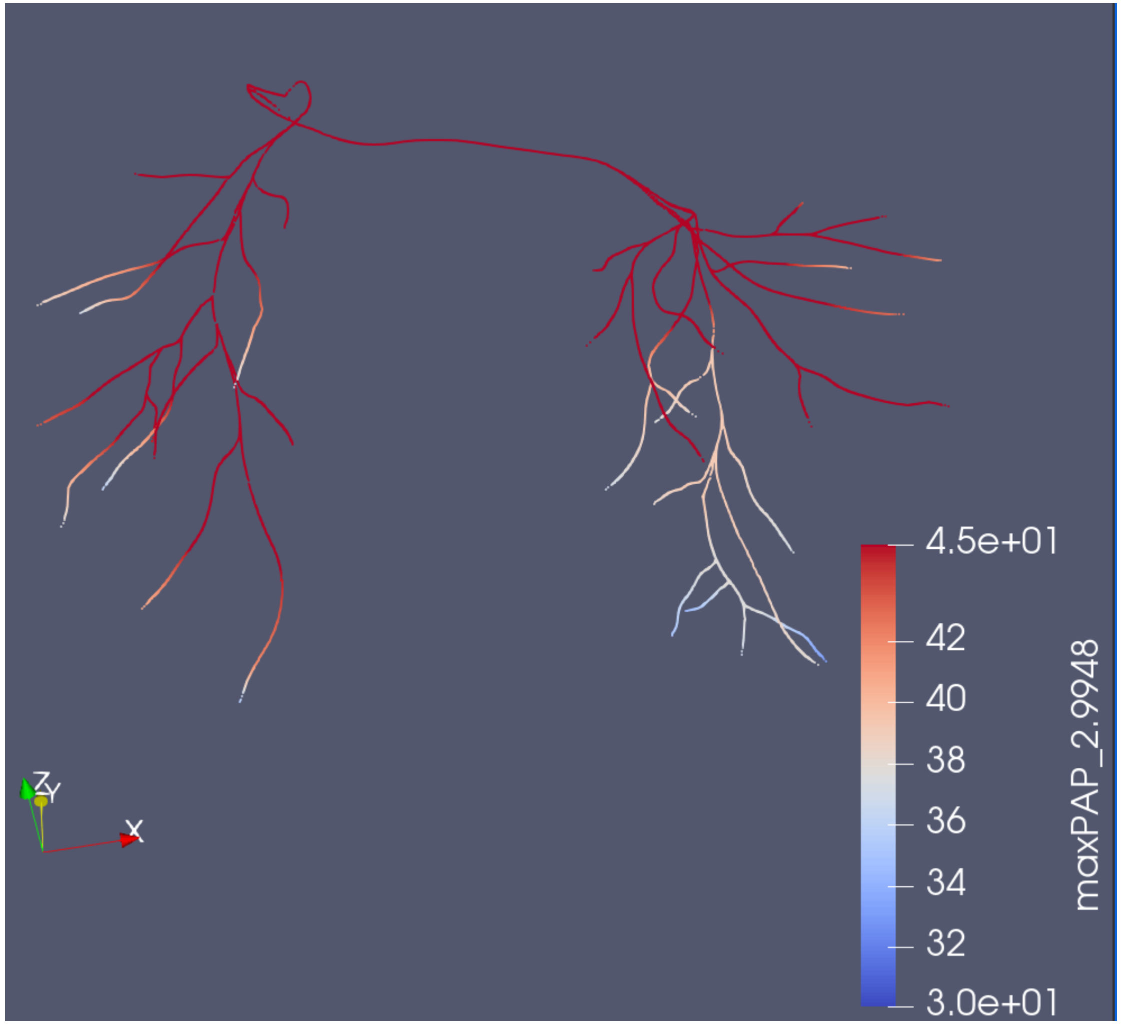


Notes:

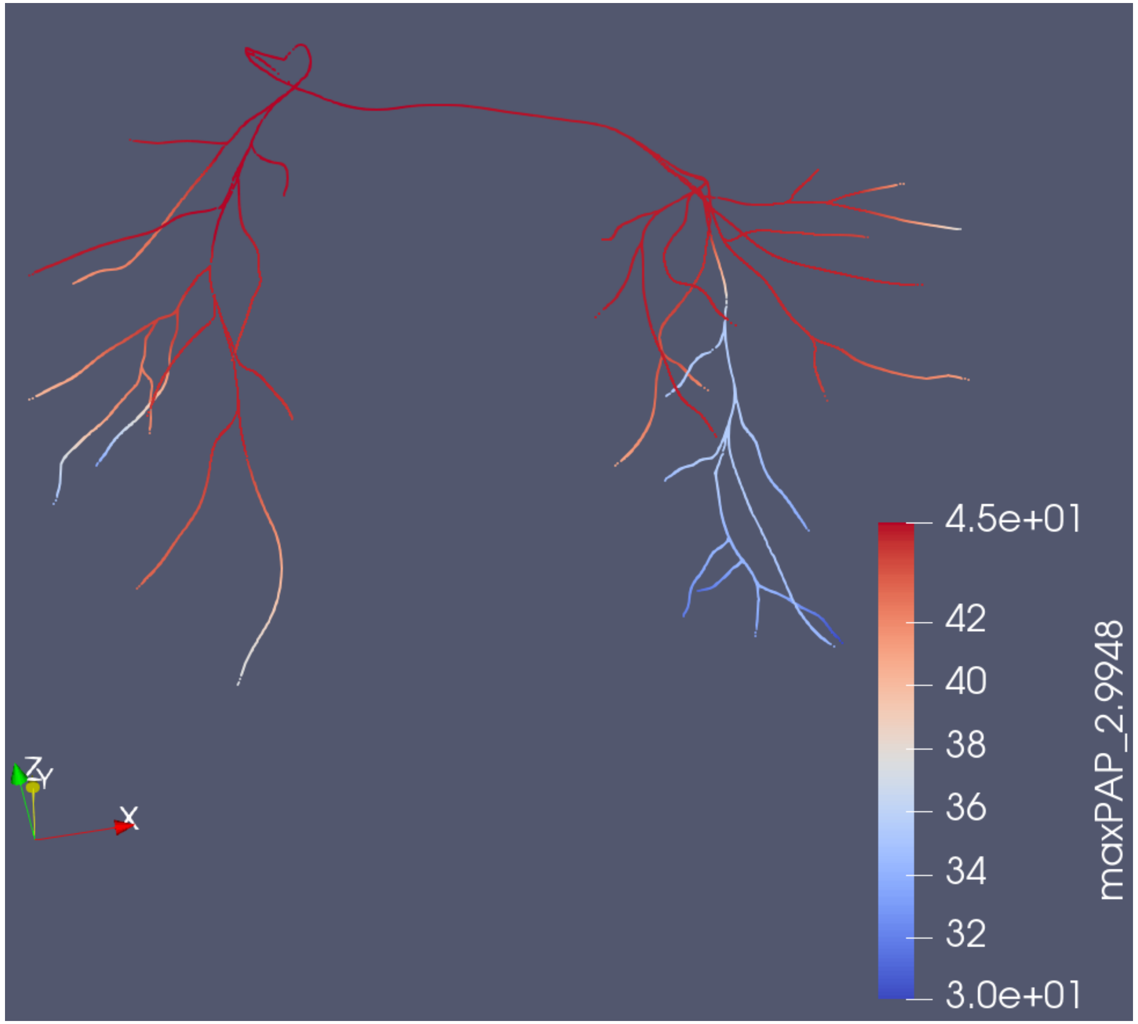
- Minor decrease

mPAP

No Fix



Fixed Stenosis



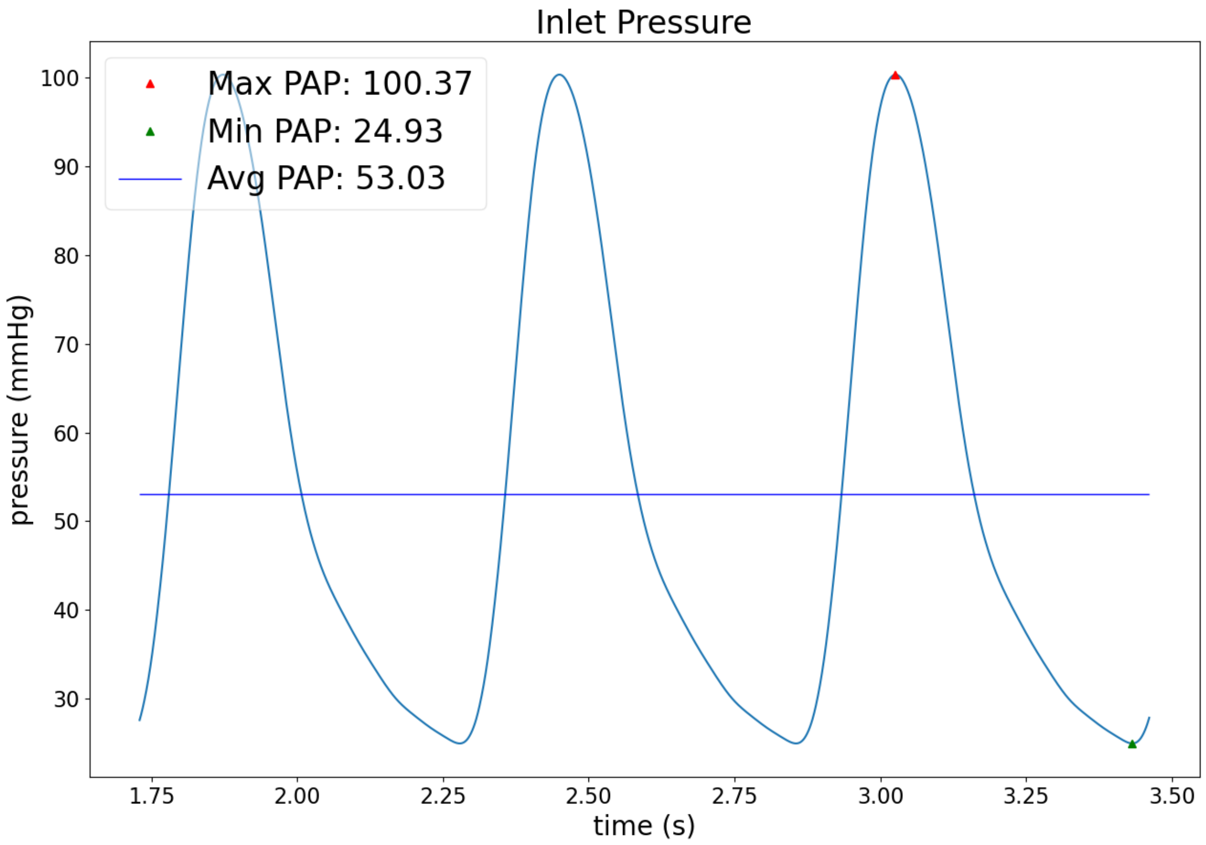
Notes:

- Minor decreases too, particularly at ends

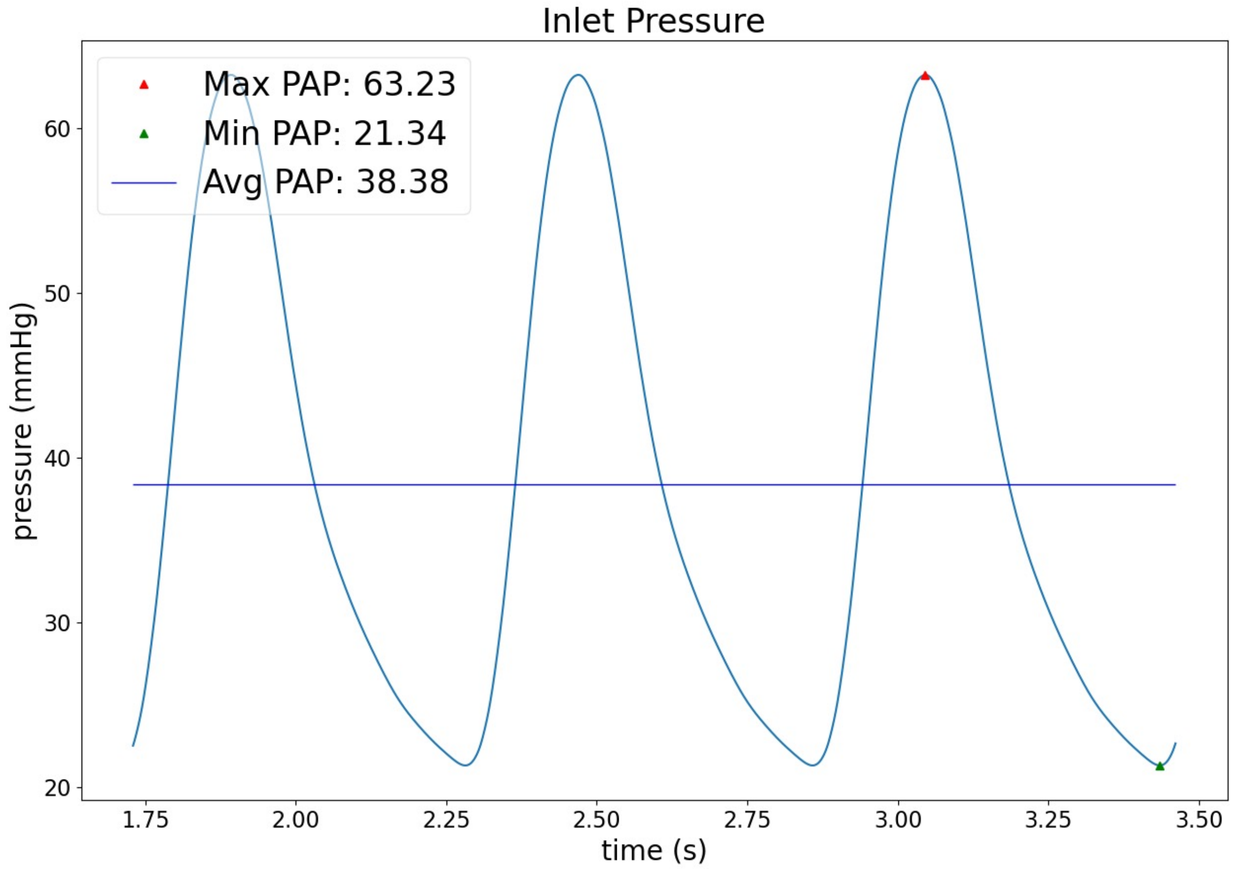
maxPAP

M1 vs. Fixed (Waveforms)

M1 Solver



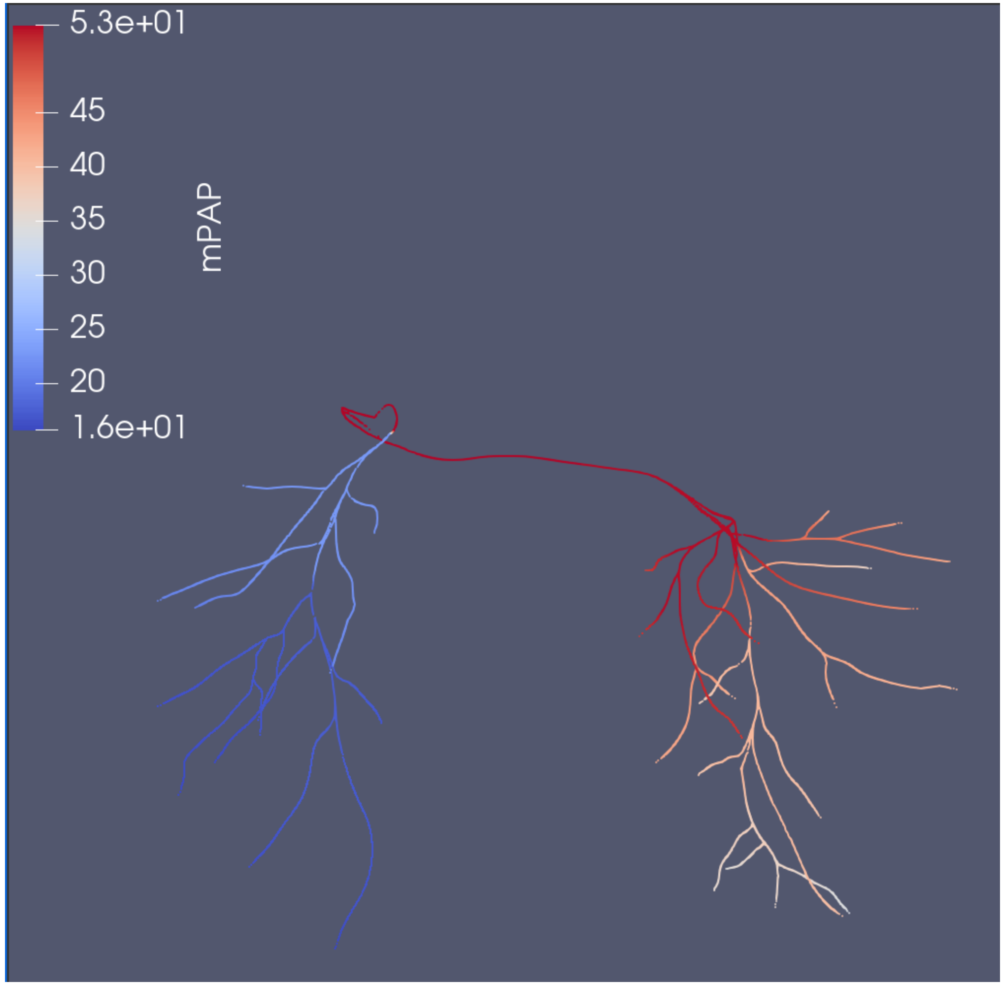
M1 Fixed Solver



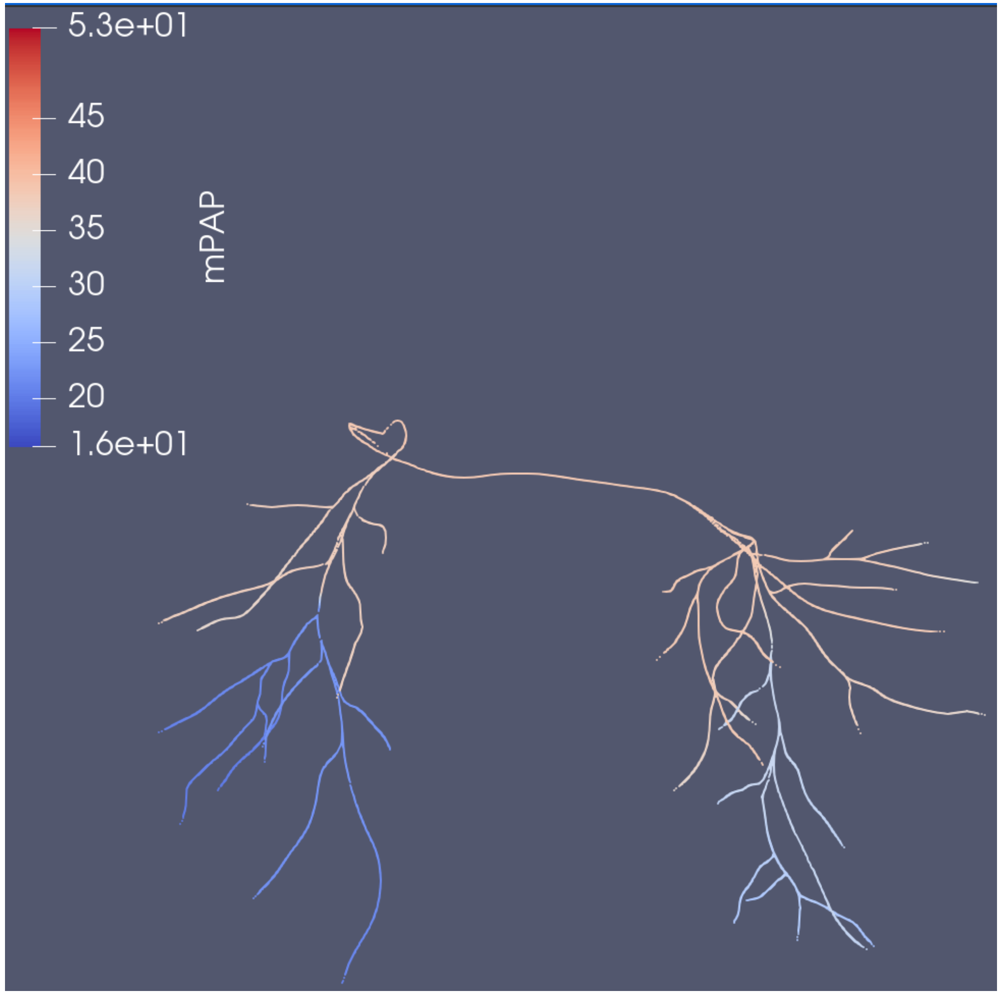
Notes:

- There is a significant reduction in all parameters, indicating positive viability for this approach.
- Also, there is actually no change in the vessels that were determined to be
- ***The fixing operation is slightly off, since it reduces the lumped stenosis coefficient in downstream branch vessels, only by the increase in the vessel’s radii, not considering the junction radii

No Fix M1



Fixed M1 Stenosis

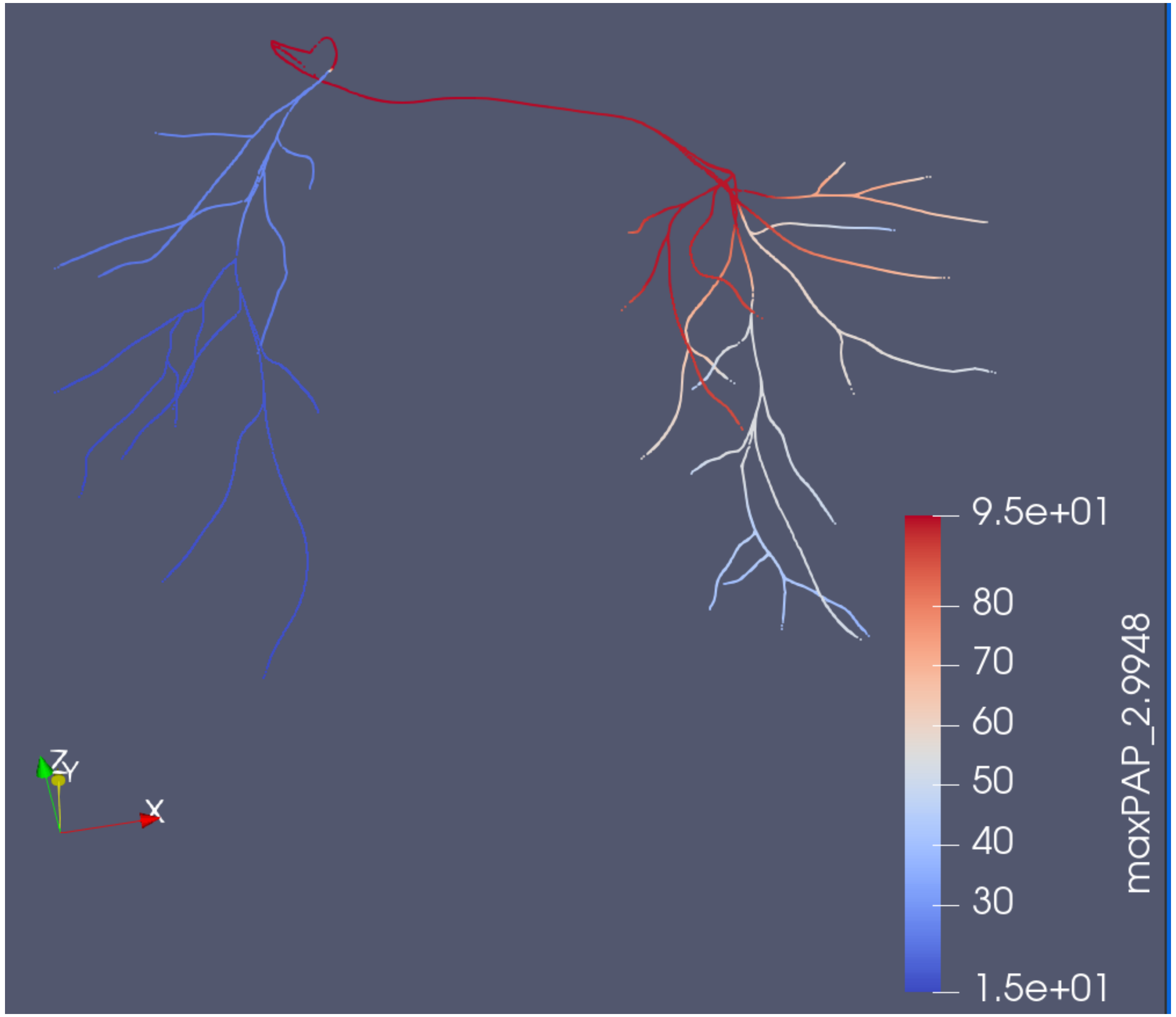


Notes:

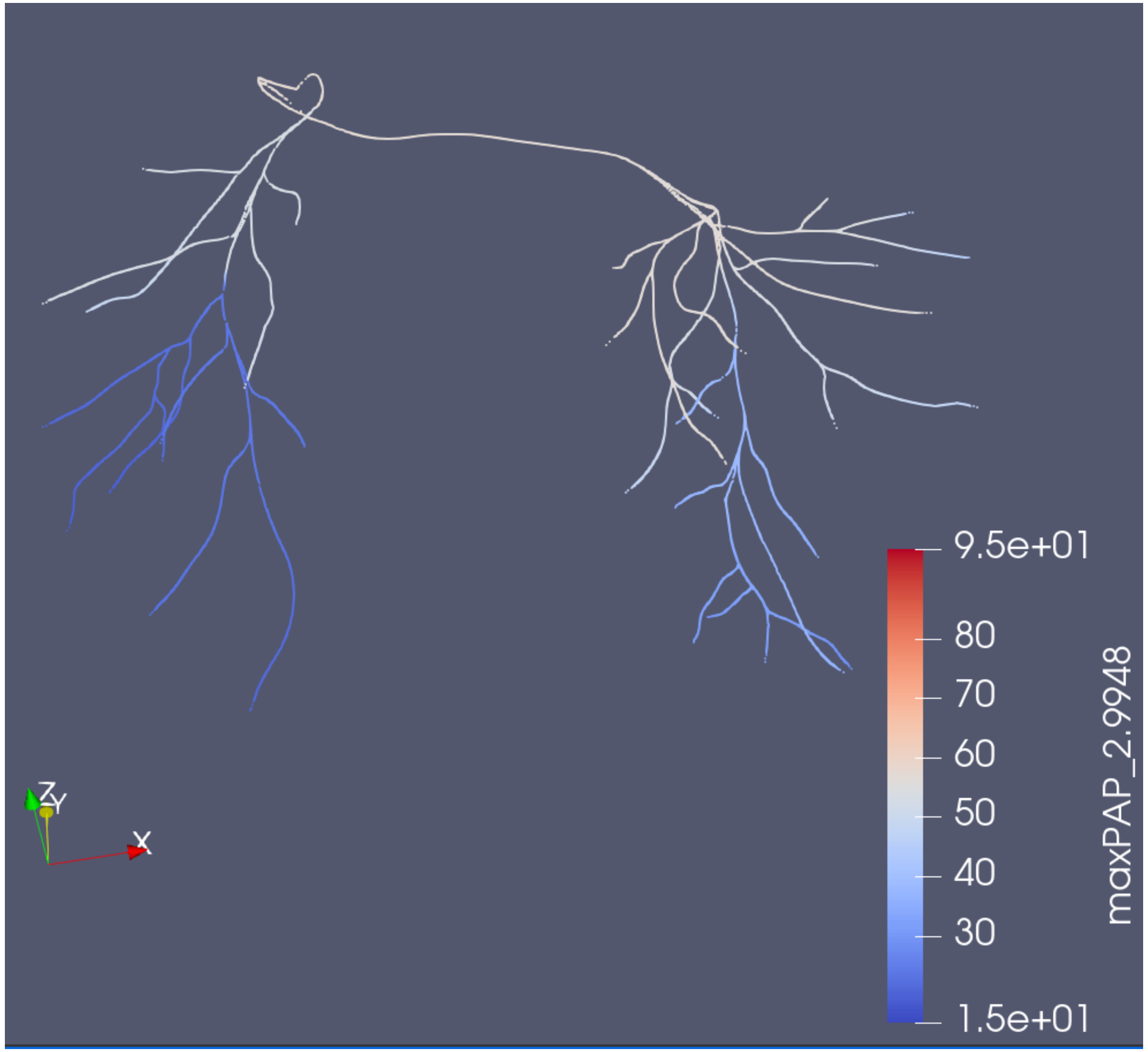
- Clear decrease in pressure, but also a more even pressure drop between LPA and RPA

mPAP

No Fix M1



M1 Fixed Stenosis



Notes:

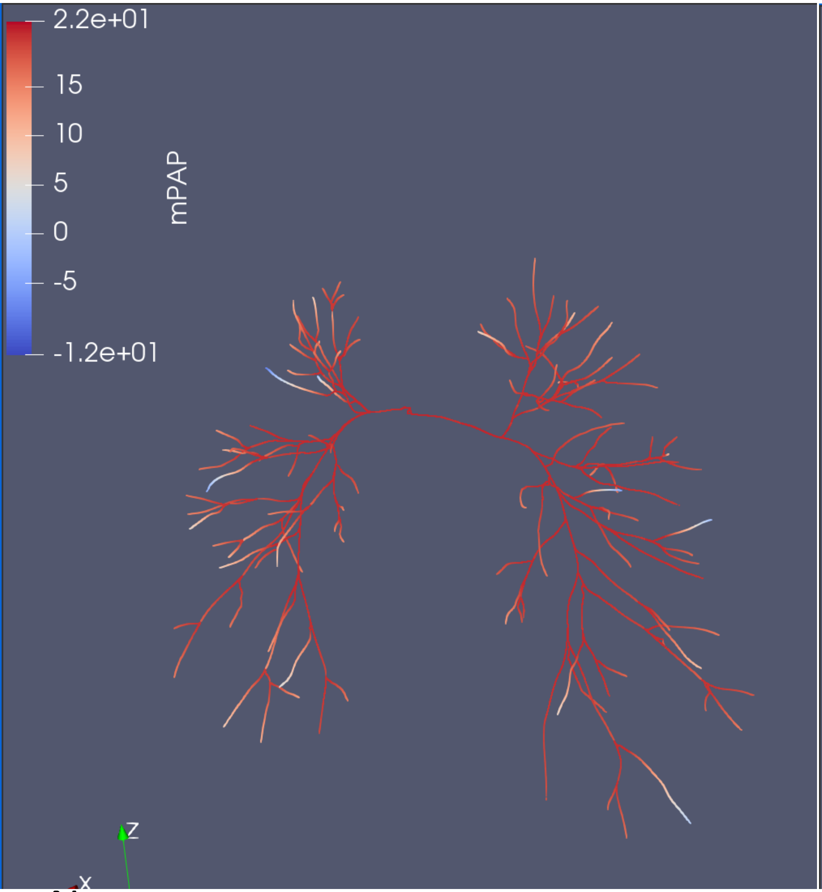
- Very large drop, with more even pressures.

maxPAP

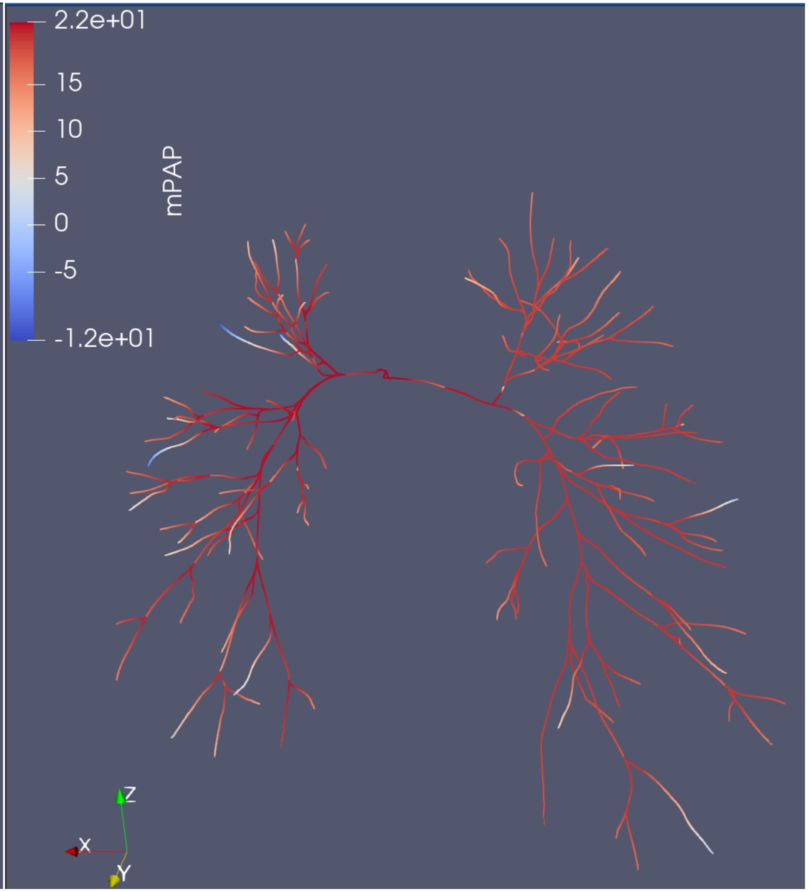
Stenosis Case Study Model – SU0238

0D vs. 3D (mPAP)

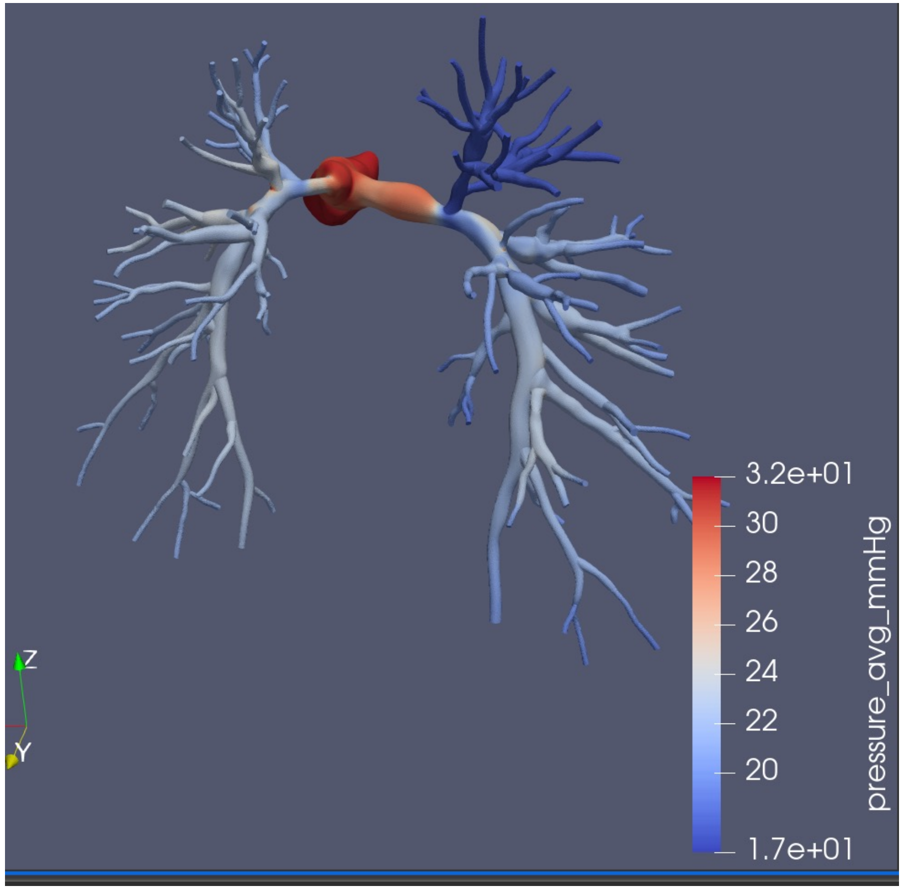
Base Solver



Method 1 (stenosis coeff)



3D



Notes:

- Branch 93, Vessel 143, *Are some places with negative flow, but the pressure drop on average for that vessel is still positive (Is there an interpolation error???) The recorded outlet pressures are all around 20, which is not a huge drop?
- Vessel by vessel, the min pressure out is around 17, (and the average pout is 19-20) which is to be expected. Hence I suggest some issue with interpolation.
- Regardless, M1 is NOT capturing the 3D solution's pressure drop.

Not to scale

Other Potential Solutions

Method 1 (being implemented)

- Computing a stenosis coefficient only using input radii and output radii of a junction. Adding stenosis coefficient to downstream vessel.
- Problems:
  - May not be a good representation. Could drastically increase stenosis coefficient if input radii is really small. (Does not seem to be a huge problem as of right now)
  - When performing stenosis fixture, it is not as easy to factor in stenosis coefficient reduction of vessel separately from the junction (doable though)
  - May have errors mapping back into centerlines (possible issue)
  - Does not work sufficiently with SU0238 (could be due to a different issue though)
- Success
  - Better representation with 0118_0001
  - Only slightly elevating 0080_1000, which is good.

Method 2

- More intensive representation of branches, rather than just stenosis coefficient to downstream vessels
- Problems
  - May require much more involved changes to input file construction and mapping back to centerlines (not too familiar with code/no access)
  - Perhaps already being planned to be implemented (Martin would know)
  - Challenging to handle, since we can’t use Poiseuille laws easily

Method 3 (Could go back and do later)

- Given the nature of my task, we can run a 3D simulation “offline” first, then construct a more accurate representation of the 0D model using actual pressure drops across branches/segments
- Could save at less number of timesteps to allow for faster computation of 3D solver, at cost of slightly less accurate optimization
- Basically optimize the RCL for each branch such that an appropriate pressure drop/flow decrease is reached.
- Problems:
  - Very time intensive/code involved. May require more familiarity with vtk
  - Concerns that 0D will not continue to match 3D if stenosis is introduced.
  - How to segment the vasculature
- Pros
  - High likely to work/be accurate

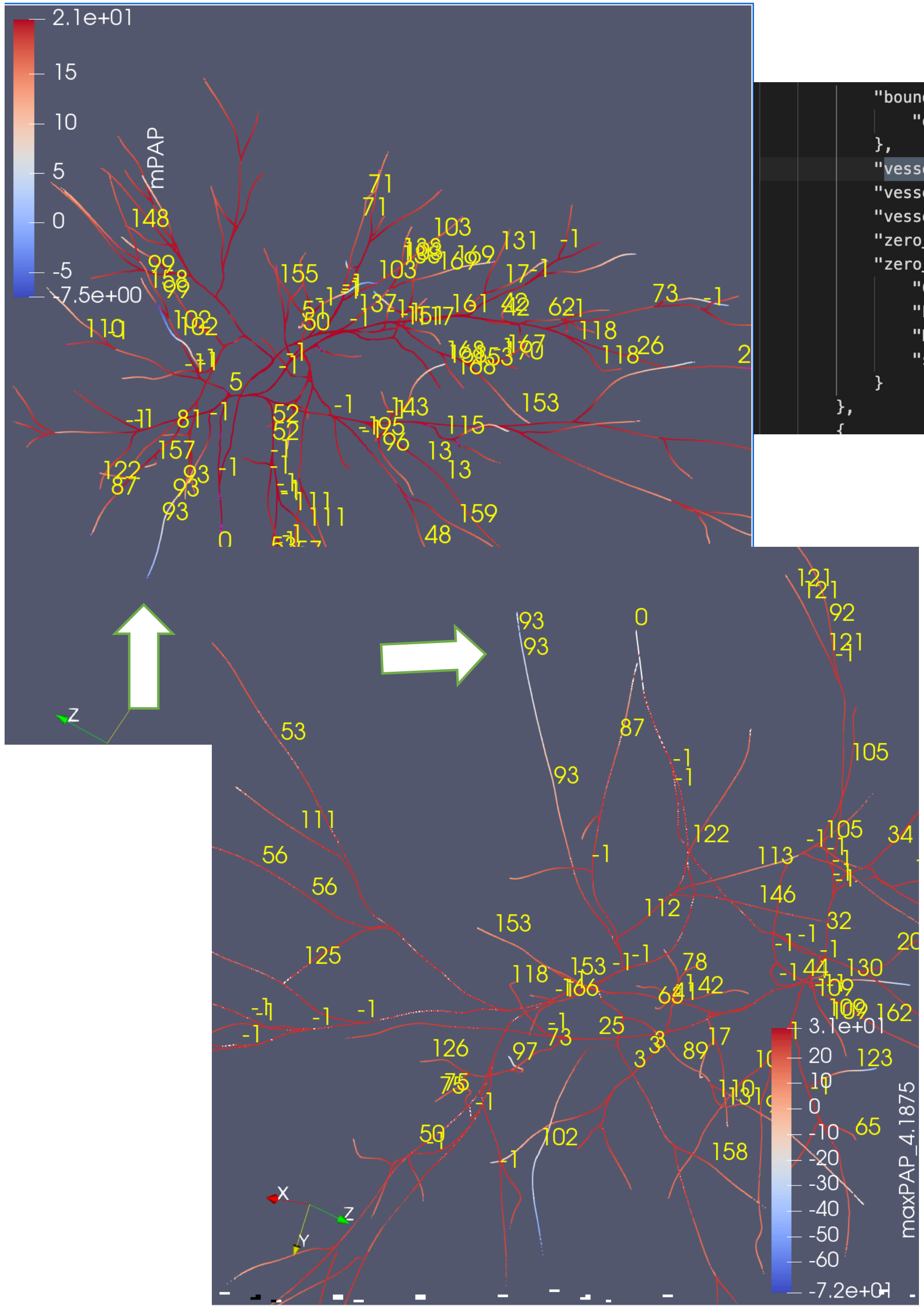
Suggestion for Next Steps

- Tinker w/ Healthy models a bit more (We can guarantee that stenosis of healthy models will solely be in the vessels, hence not encountering the junction stenosis issue)
  - Generate more models/case studies for healthy models.
  - (~1 week, assuming no major issues)
- Construct Neural network for 0D simulations on healthy models.
  - (~1 week)
- Compute Probabilities/Build tool
  - (Back at ND)
- *Uncertainty computation?
  - (Back at ND)
- *Go back and implement Method 3.

Next Steps (Neural Network)

- Construct NN capturing the changes in pressures and flows depending on the change in resistance
- Sample from resistance space using Sobol Sampling

- Compute Probabilities

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    "zero_d_element_type": "BloodVessel",
    "zero_d_element_values": {
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        "L": 20.827480453374726,
        "R_poiseuille": 944.7778480158622,
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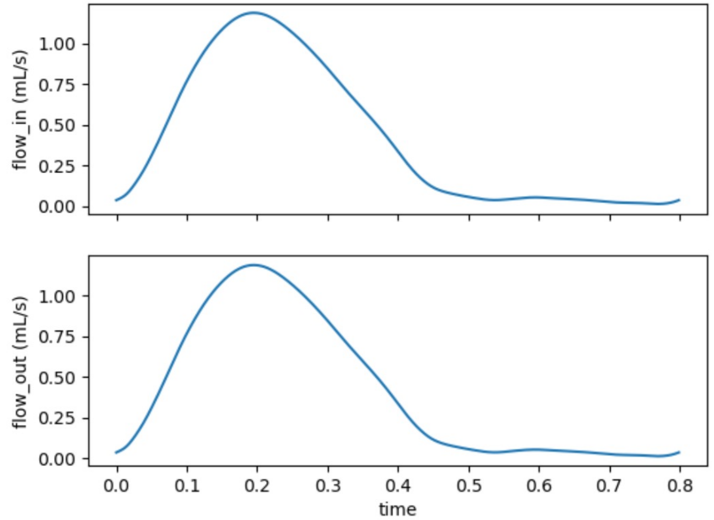
Flows V143



Pressures V143