Computational Model Validation for Upper Airway Turbulent Mixing Study

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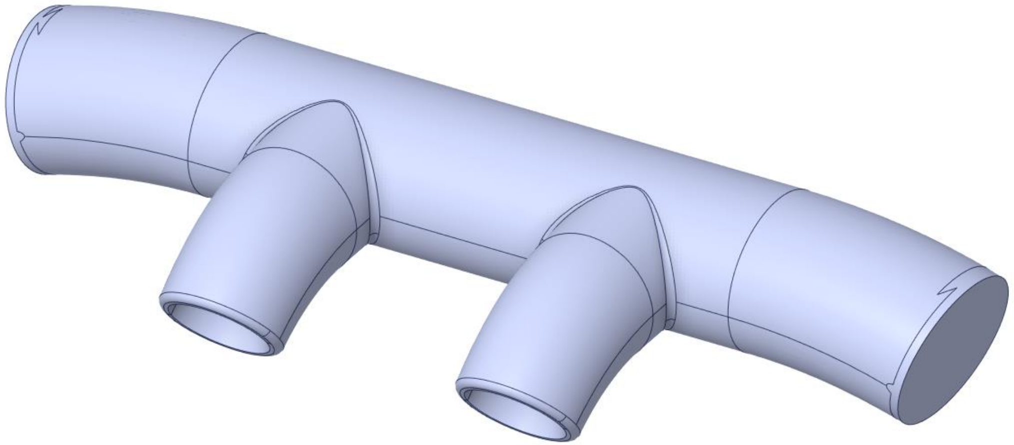
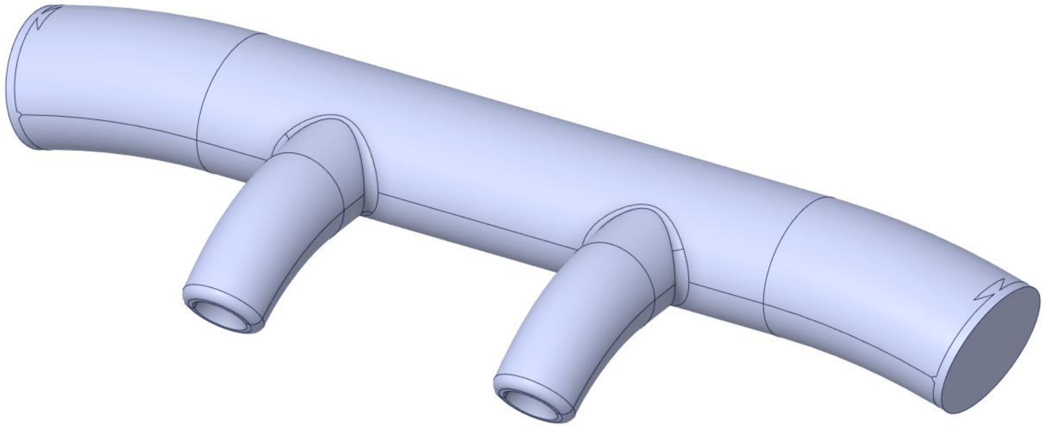
For more information on our research, visit our webpage at
www.fluidgroup.org

Background

- High Flow Nasal Cannula (HFNC) Oxygen Therapy
  - Non-invasive respiratory therapy delivering heated, humidified oxygen via a nasal cannula
- High Velocity Nasal Insufflation (HVNI)
  - Subset of HFNC oxygen therapy in which the flow is delivered at higher velocities



HFNC geometry



HVNI geometry

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Current State/Objective

- Prior research has had deficiencies in at least one of the following areas:
  - Breathing conditions not representative of a real patient
  - **Poor or non-existent validation discussion**
- This study aims to create a novel computational model to be used for studies examining effectiveness of non-invasive respiratory therapies

Important Definitions

- Timestep
  - The temporal progression between moments in which the governing equations are solved
  - Imagine frames per second of a video
- Mesh
  - A geometry that is broken down into many smaller components (cells)
    - This allows the governing equations to be assigned to individual cells
  - Imagine picture resolution
- Solution efficiency can be maximized using independence studies

Validation Methodology

Collect experimental O_2 information using 3D printed airway geometry and ASL5000 breathing simulator

→

Establish numerical independence

- Timestep independence
- Mesh independence

→

Compare O_2 data for all models to experimental data and draw conclusions

Meshing

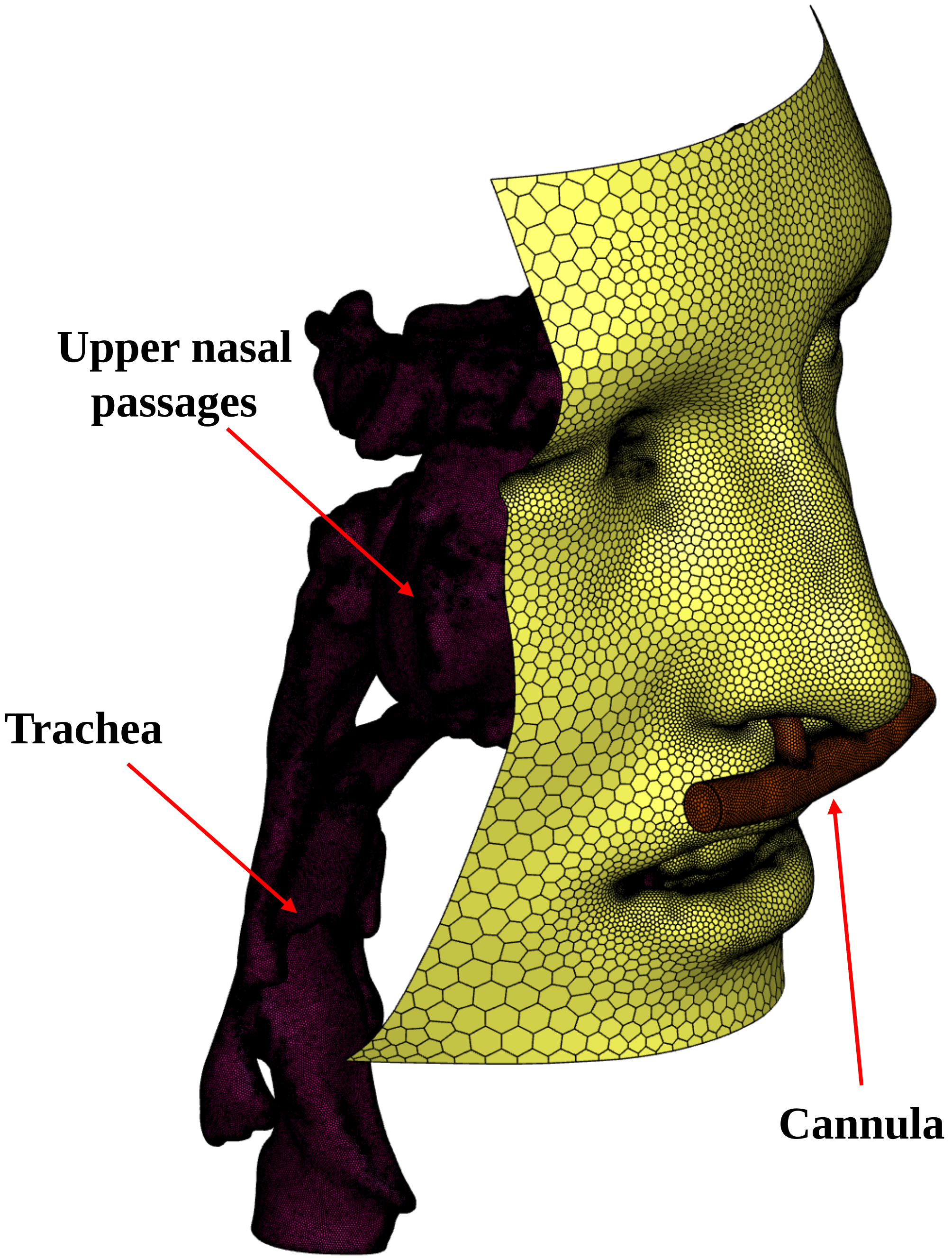
CT Scan
- Collect CT scan of patient airway

Slicer
- Create 3D geometry file from patient CT scan

SpaceClaim
- Implement cannula geometry and modify patient airway to be suitable for meshing

Fluent Meshing
- Generate mesh using unstructured polyhedral meshing workflow

Fluent Solver
- Import generated mesh and perform cleanup before applying boundary conditions



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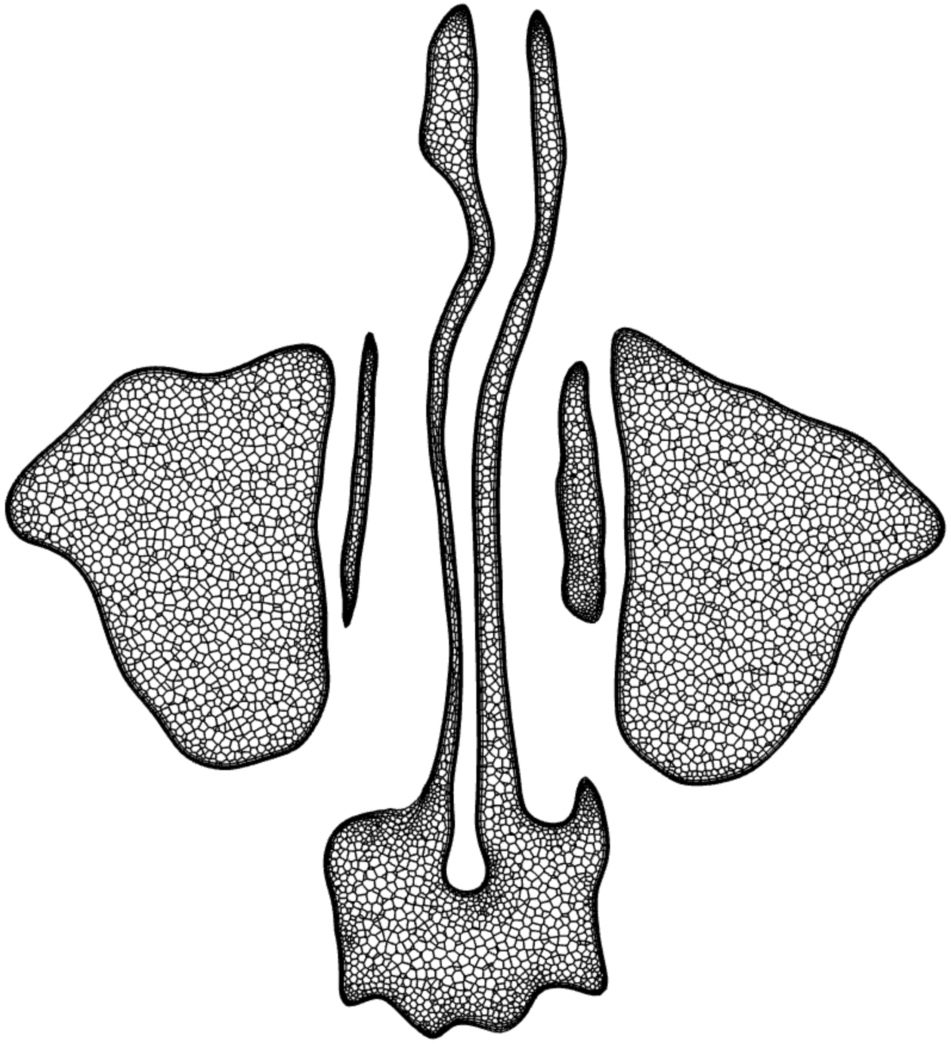
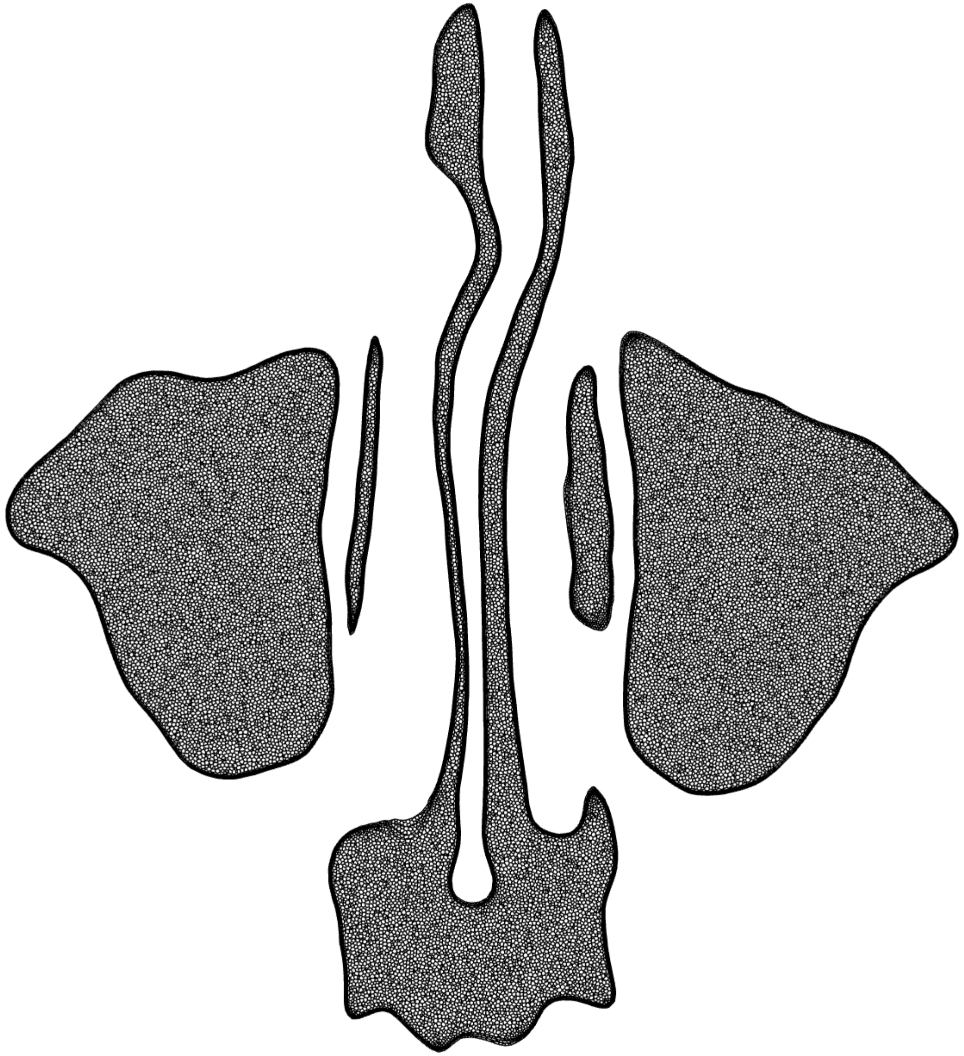
Mesh Examples



~2 million cells



~8 million cells

Note: Cross sections collected at the same arbitrary location in the fluid domain

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Boundary Conditions

Airway "Inlet"

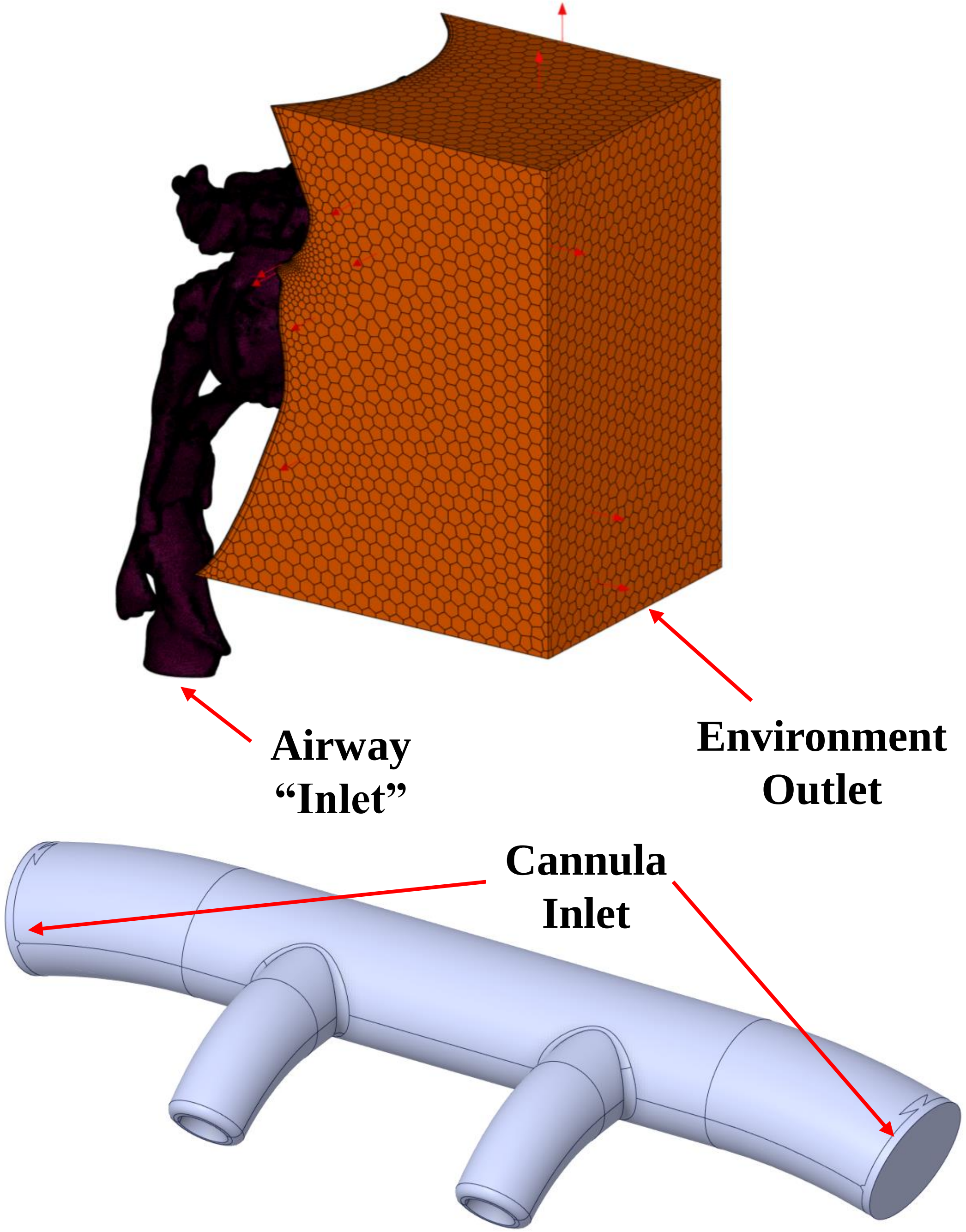
- Variable velocity boundary controlling:
  - Volume flow rate
  - Species concentrations

Cannula Inlet

- Steady input of 100% O_2 at 35 standard liters per minute

Environment Outlet

- Pressure outlet with species feedback of 0.21 mole fraction O_2 (ambient air)



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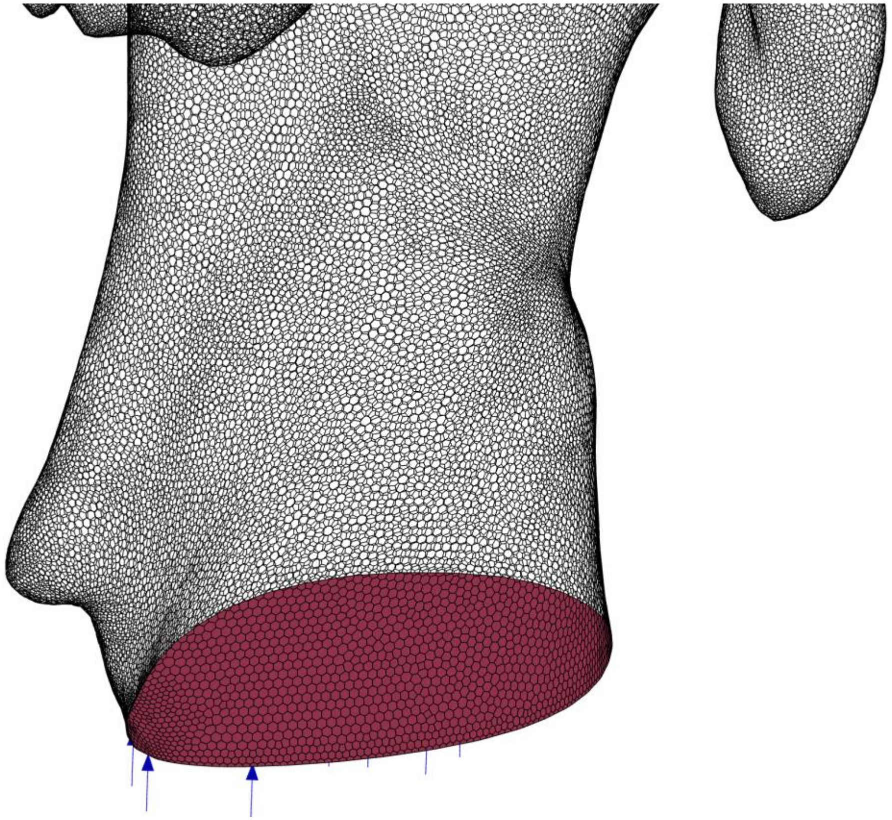
Modeling Methodologies

Lower Rigor (LR)	Higher Rigor (HR)
• $k-\omega$ (SST) turbulence model • Baseline discretization schemes and transient formulation	• Differential Reynolds Stress (DRSM) turbulence model • Higher rigor discretization schemes and transient formulation • Less numerical diffusion • Higher computational cost than LR

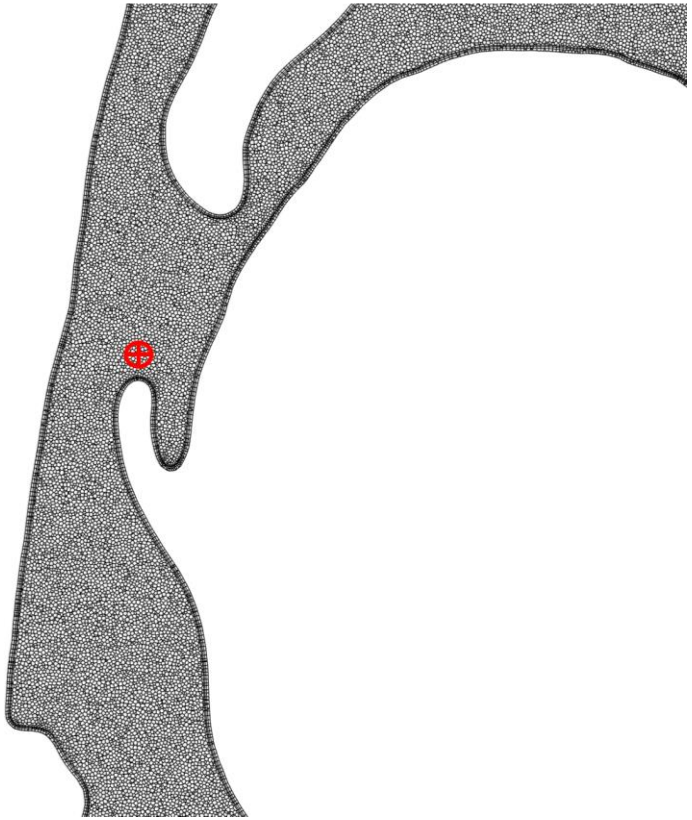
- Data will be analyzed for each group of settings to see if higher computational cost of HR is outweighed by improvement in performance

Coarse vs Fine Measures

Coarse



Fine



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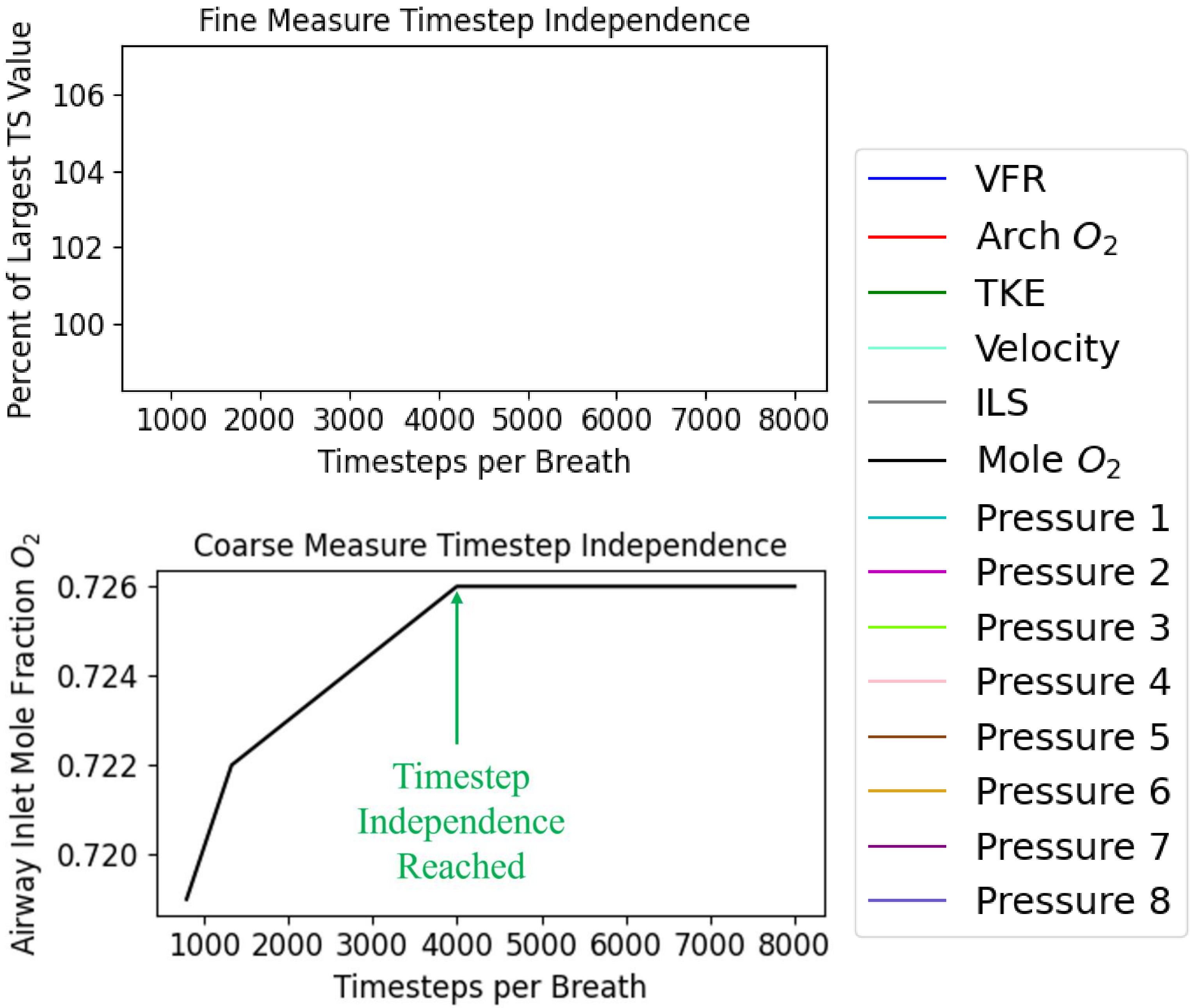
Timestep Independence

- Fine measures show acceptable variation
- Coarse measures steady out after 4000 timesteps per breath



- VFR = Volume Flow Rate
- TKE = Turbulent Kinetic Energy
- ILS = Integral Length Scale

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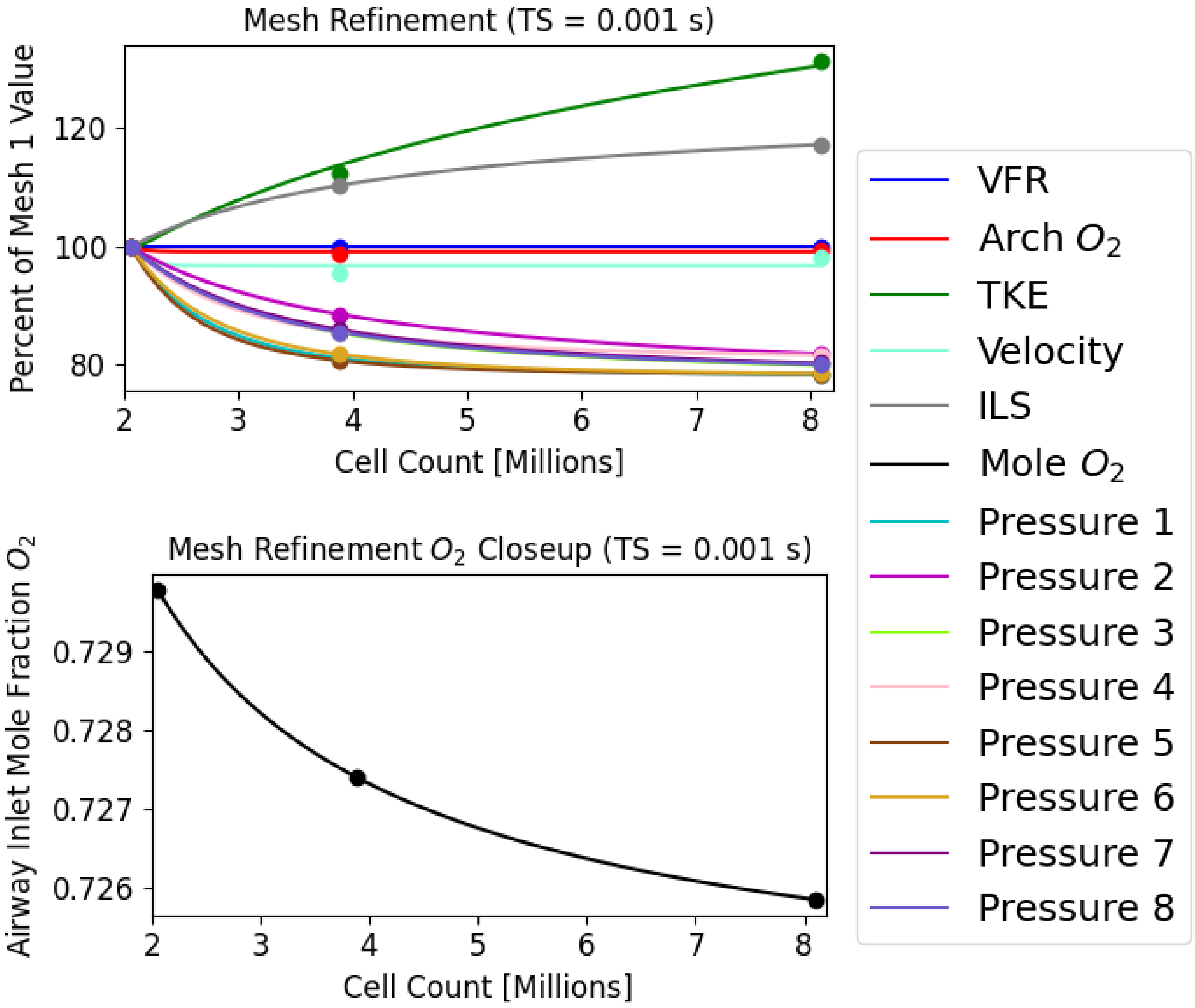
LR Mesh Independence

- Mesh considered to be of acceptable refinement at mesh 3 (8 million cells)
- Surprisingly, little movement is seen in turbulence metrics (TKE and ILS)
- Coarse measurement (Mole fraction O_2) shown in individual plot
- O_2 trend is counter-intuitive



- VFR = Volume Flow Rate
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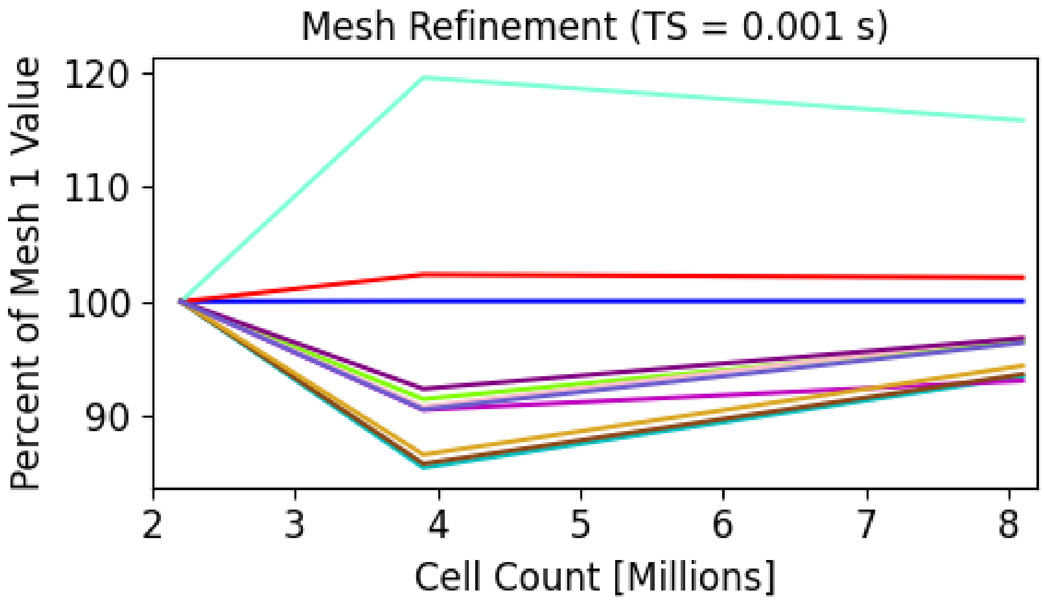
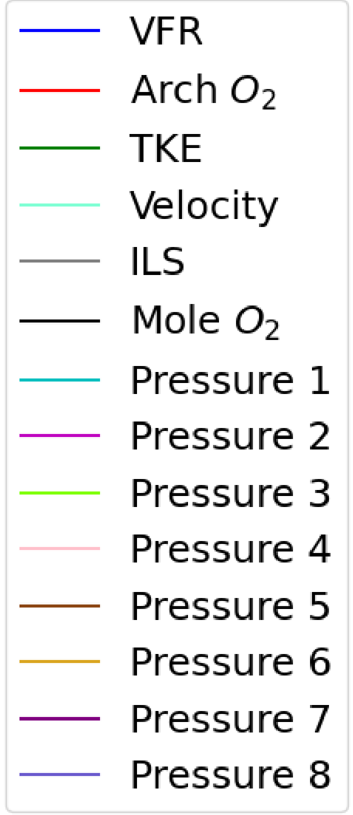
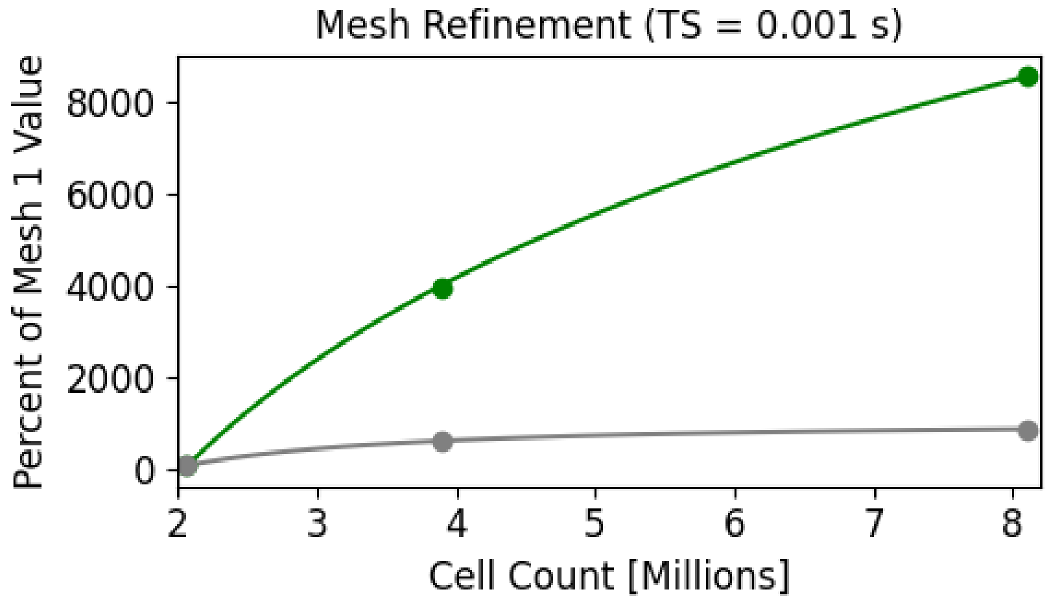
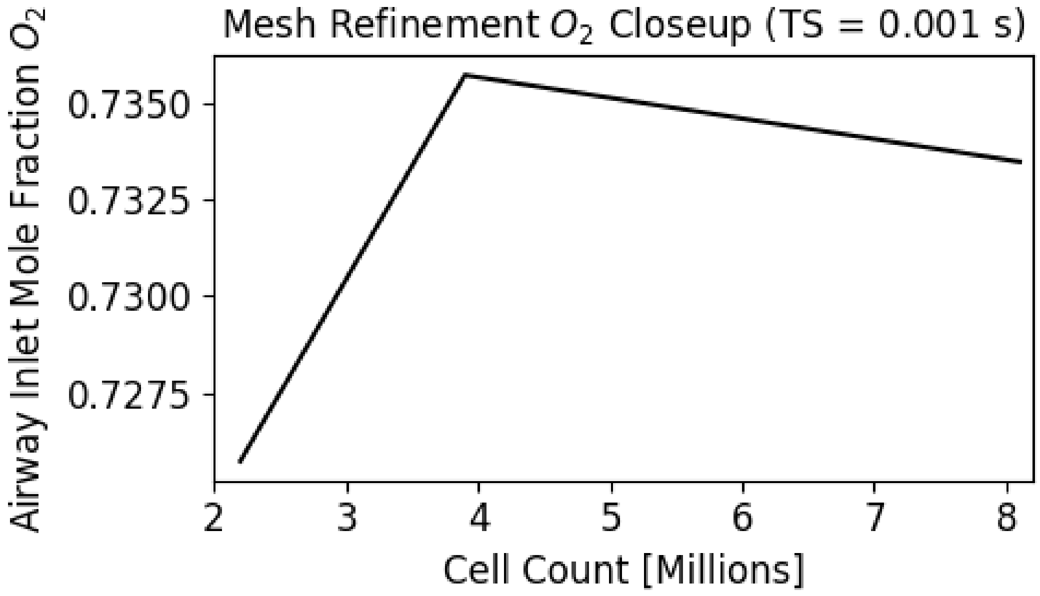
HR Mesh Independence

- Significantly higher change in turbulence metrics with mesh refinement
- O_2 trend follows what we would expect









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Results Summary

- Final validated model shown in green
- Notice that there are 2 models closer to the experimental value that have not reached numerical independence
  - Highlights the dangers of poor validation methodology

Model	Mole Fraction O_2
Experimental	0.738
HR-M1-4000	0.737
LR-M1-128	0.735
HR-M3-4000	0.734
LR-M1-4000	0.731
HR-M3-4000	0.730
LR-M3-8000	0.726
LR-M3-4000	0.726
LR-M2-4000	0.726
LR-M3-1333	0.722
LR-M3-800	0.719

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Conclusions

- The final validated model can be used for further studies examining non-invasive respiratory therapy
- The validation process **must** include establishment of numerical independence **using fine grained measurements**
  - If only coarse measurements were considered, numerical independence would have been established prematurely

Any Questions?

Declaration of Mesh Independence

- The general trends seen in both mesh refinement studies point towards little further changes in calculated measurements
  - LR shows asymptotic trends that are heavily flattening by mesh 3
  - HR shows nearly asymptotic trends with some acceptable sign change between mesh 2 and mesh 3
- Two separate mesh refinement studies were conducted
  - This means all additional datapoints for mesh refinement had to be run with 2 different settings
- Sponsor deadlines promoted moving forward from validation to collect information concerning CO_2 flush