3-D Model of the Human Respiratory System

Dr. Jacky Ann Rosati Rowe, Principal Investigator
U.S. EPA, Office of Research and Development (ORD)

Ray Burton and Wei Tang, Applied Research Associates (ARA) and Rob McCauley, CSRA

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Introduction

- Developed 3-D computational fluid dynamics (CFD) model of the human respiratory system that allows for the simulation of particulate based contaminant deposition and clearance, while being adaptable for age, ethnicity, and sex.

- Model is based on human scan data and incorporates the extrathoracic region, as well as the tracheobronchial and peripheral airways of the lung. It provides the ability to modify internal face morphology to match external facial features, thus allowing for model customization. It also allows for both oral and nasal breathing, as well as variable breathing patterns.

- Progress towards parameterization for other variables that define airways, breathing patterns or deposition and clearance patterns including:
  - morphological changes created by respiratory disease,
  - dynamic physiologies to mimic anatomical changes of the respiratory system during a breathing cycle
  - mucociliary action and
  - the incorporation of functional alveoli
- Child data expected to be incorporated in 2018.

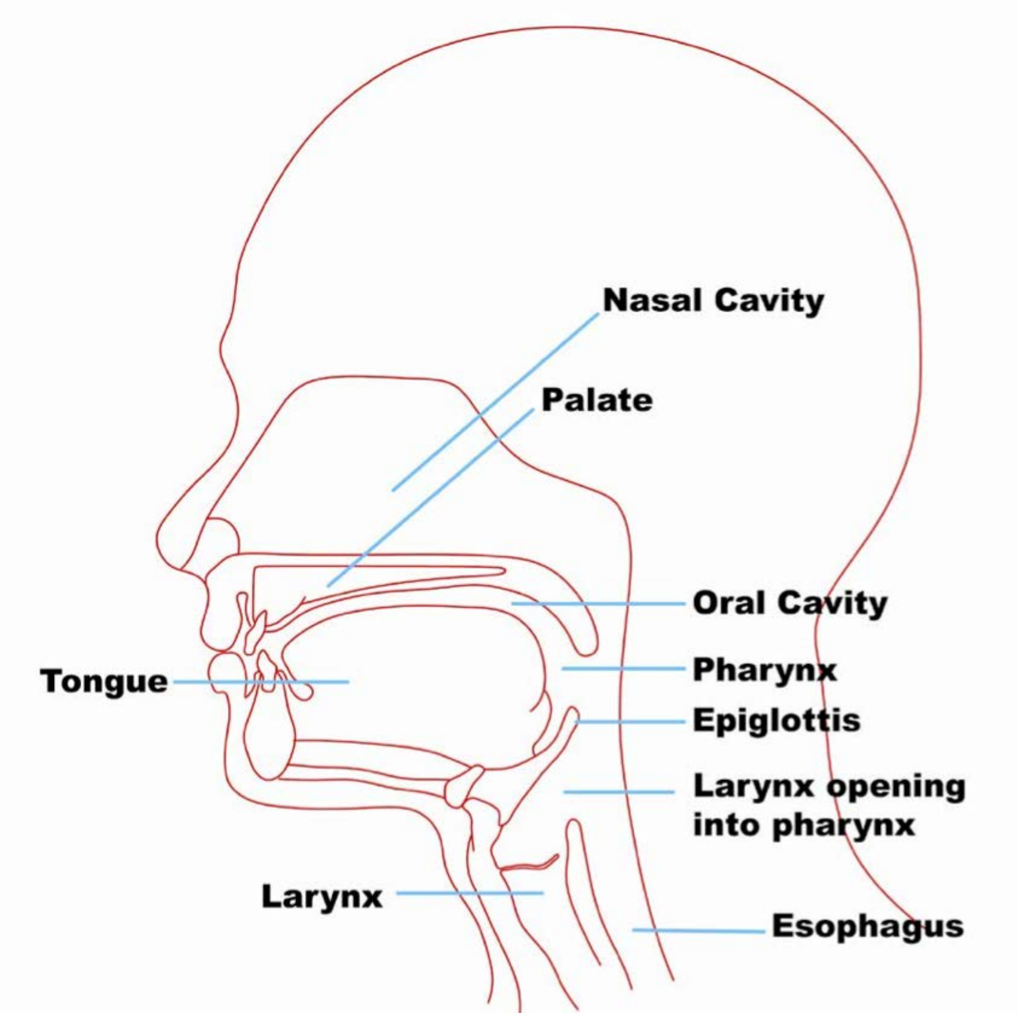
Model Uses

May be used in the investigation of:

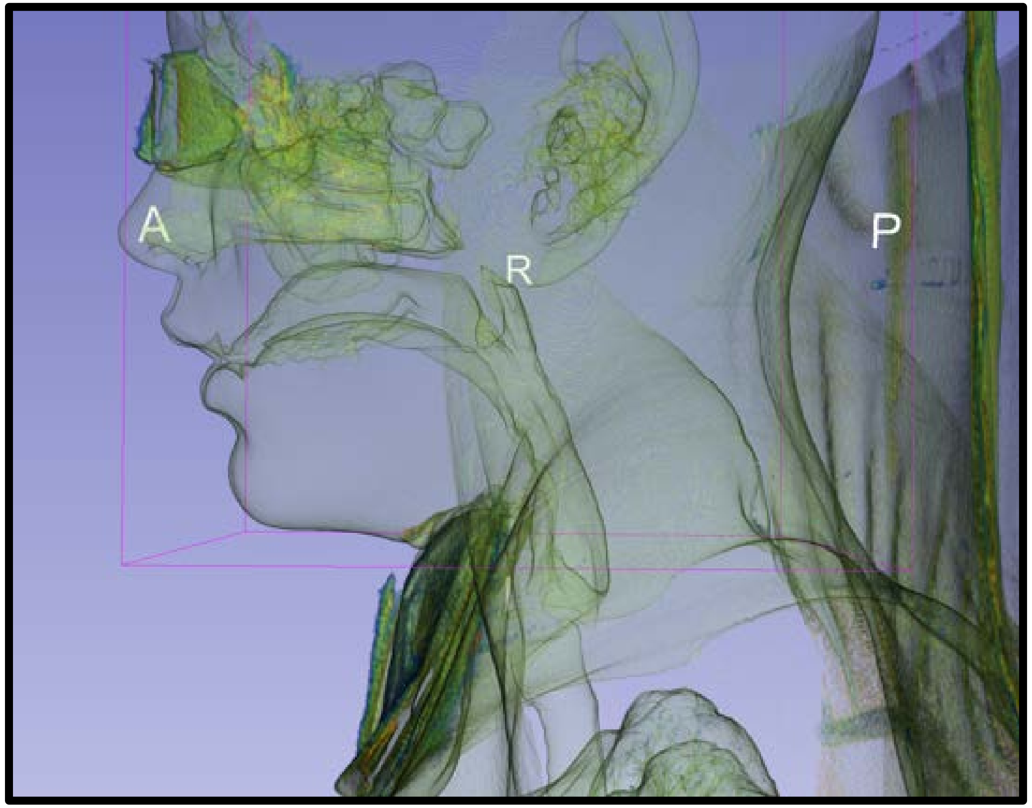
- dosimetry and inhalation toxicology for general and sensitive populations such as the diseased and the elderly.
- therapeutic purposes such as drug delivery
- determination of exposure to/dose from hazardous contaminants (e.g., anthrax, ricin) where inhalation studies on humans cannot be conducted.
- oral/nasal/lung surgery and lung transplantation planning

- Have the additional benefit of reducing animal and human use in testing, as well as testing costs.

Model Development



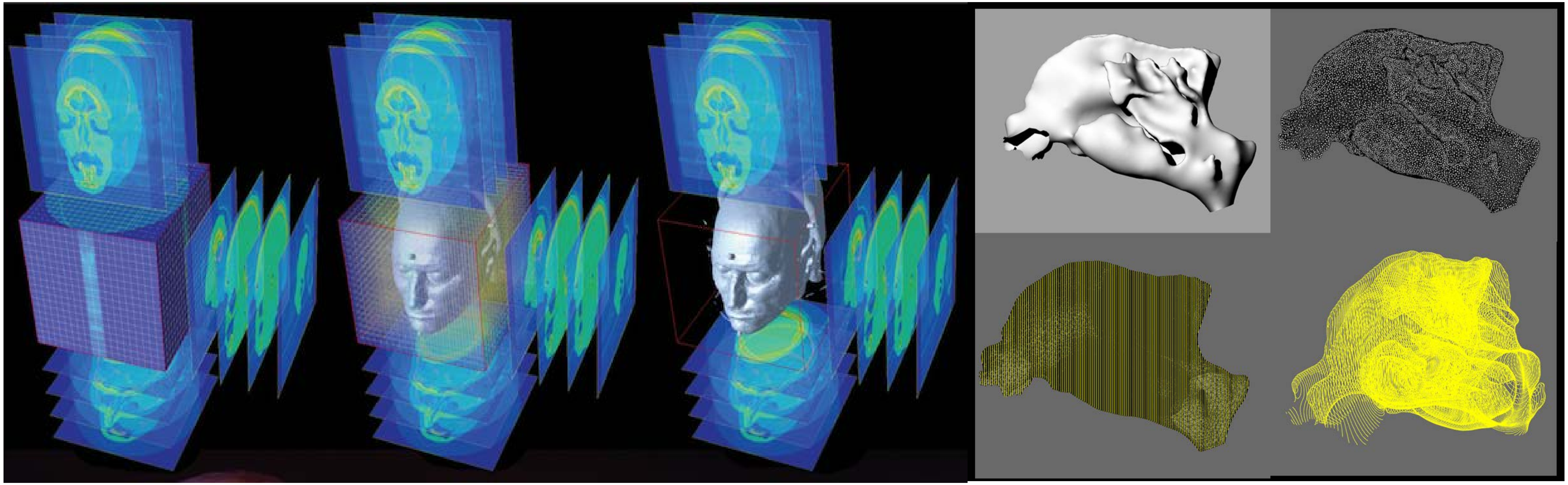
Schematic of Extrathoracic Airway



Soft tissue Extracted from De-identified Stacked CT Scan Data

Model Development - Head

- Head structure created from human data by combining a series of CT image slices.
- Three-dimensional surface of underlying soft tissue structure developed.
- The nasal and oral cavity are extracted from the structure for functional model use.



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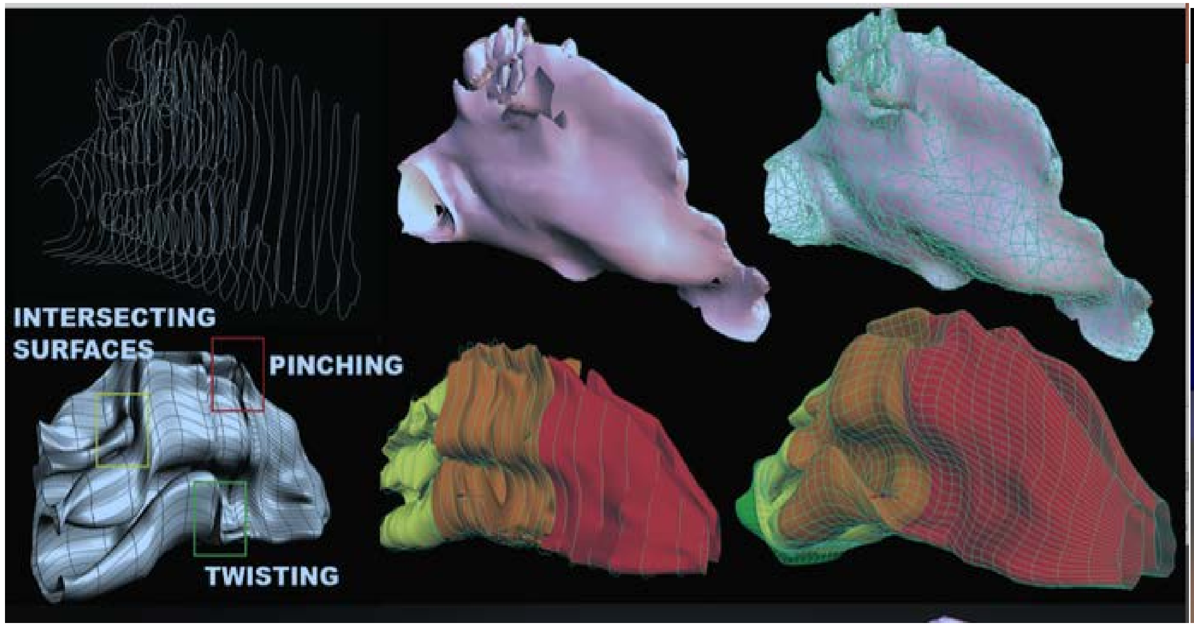
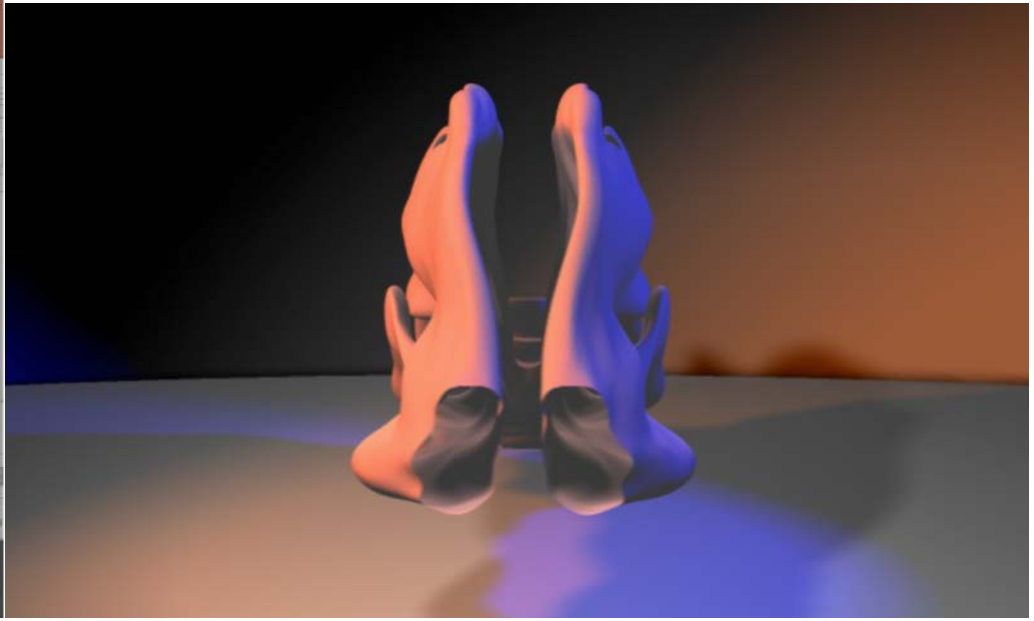
Model Development – Nasal Passages

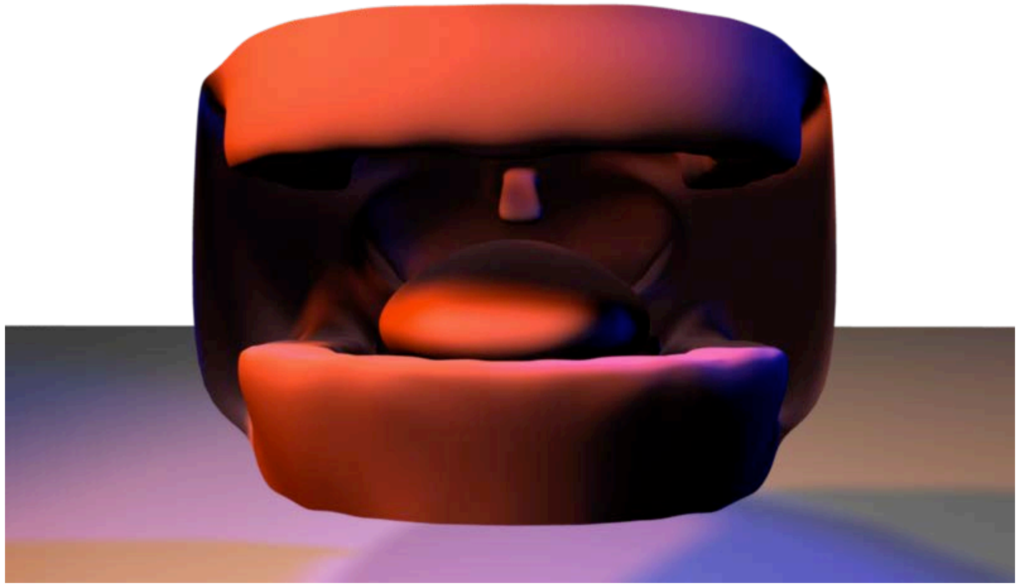
Digital geometry processing used to generate three-dimensional volume mesh of the inside of the nasal passages from two-dimensional radiographic images taken around a single axis of rotation.

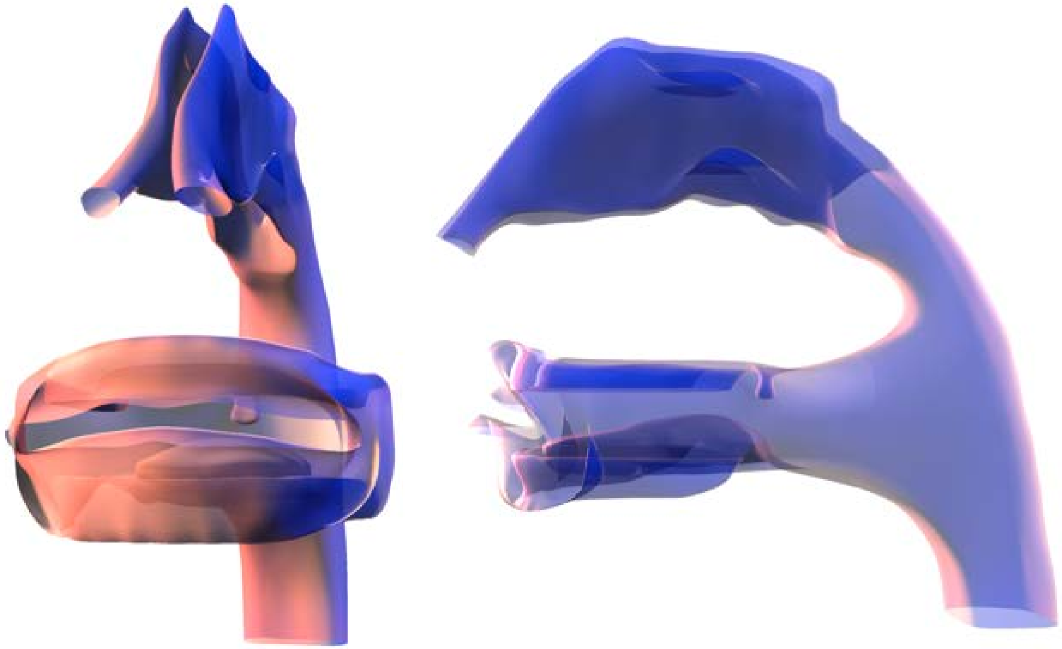




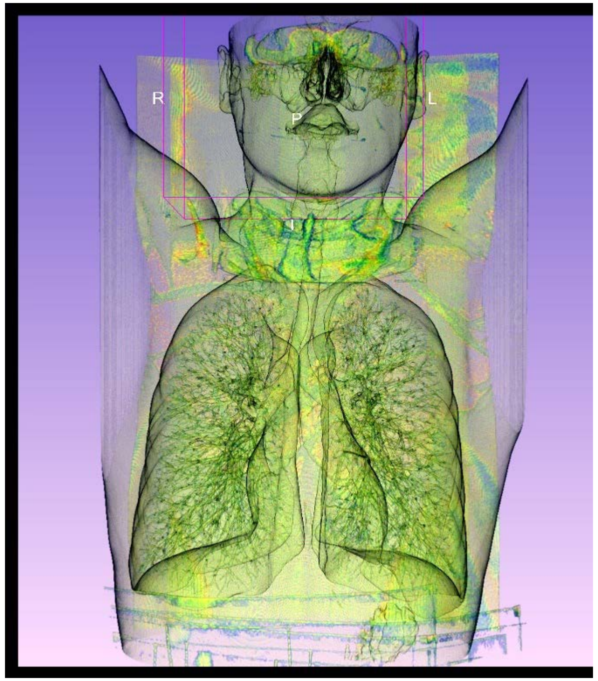
Model Development – Nasal and Oral

- The nasal cavity was extracted from the volume mesh and isolated.
- The dental plate was used as a reference mesh for the creation of the oral cavity including the gums, tongue and uvula.
- The nasal and oral cavity were combined to form a single simulation of the human upper airway system.





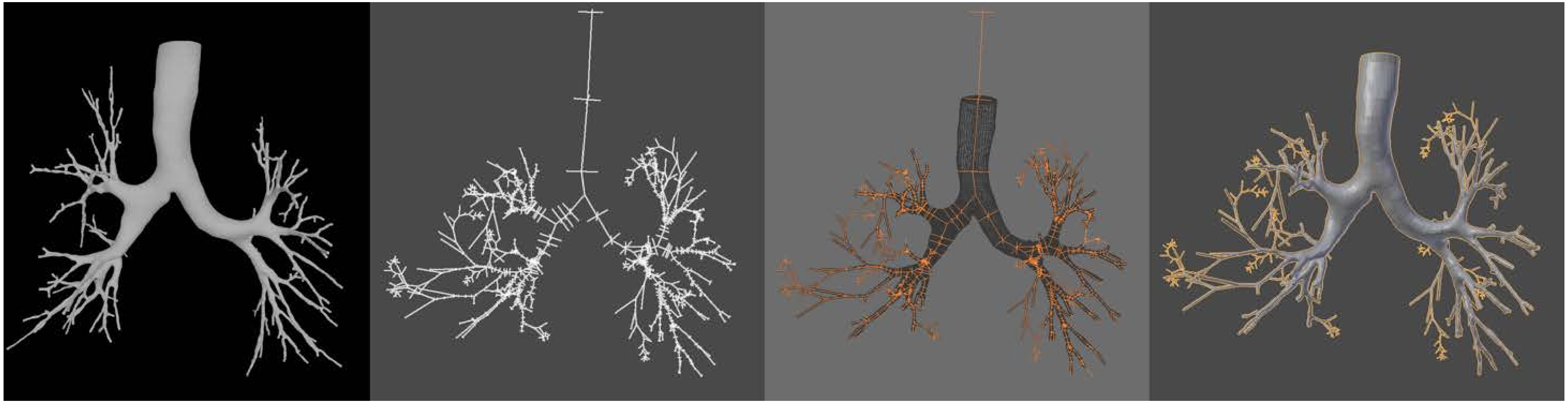
Model Development – Lung



CT Data from De-Identified Human Subject

- CT data from a human subject was used to develop a surface mesh for lung generations down to 10.
- Airway paths that were not defined by subject data (paths > 10^{th} generation) were generated randomly along airway center lines based on typical airway lengths, diameters, and bifurcation angles as reported in Yeh and Schum, 1980.
- Model supports scaling all airways, a feature that is enabled by modeling the airway geometry as simple geometric objects which define a complex surface geometry.

Model Development – Lung



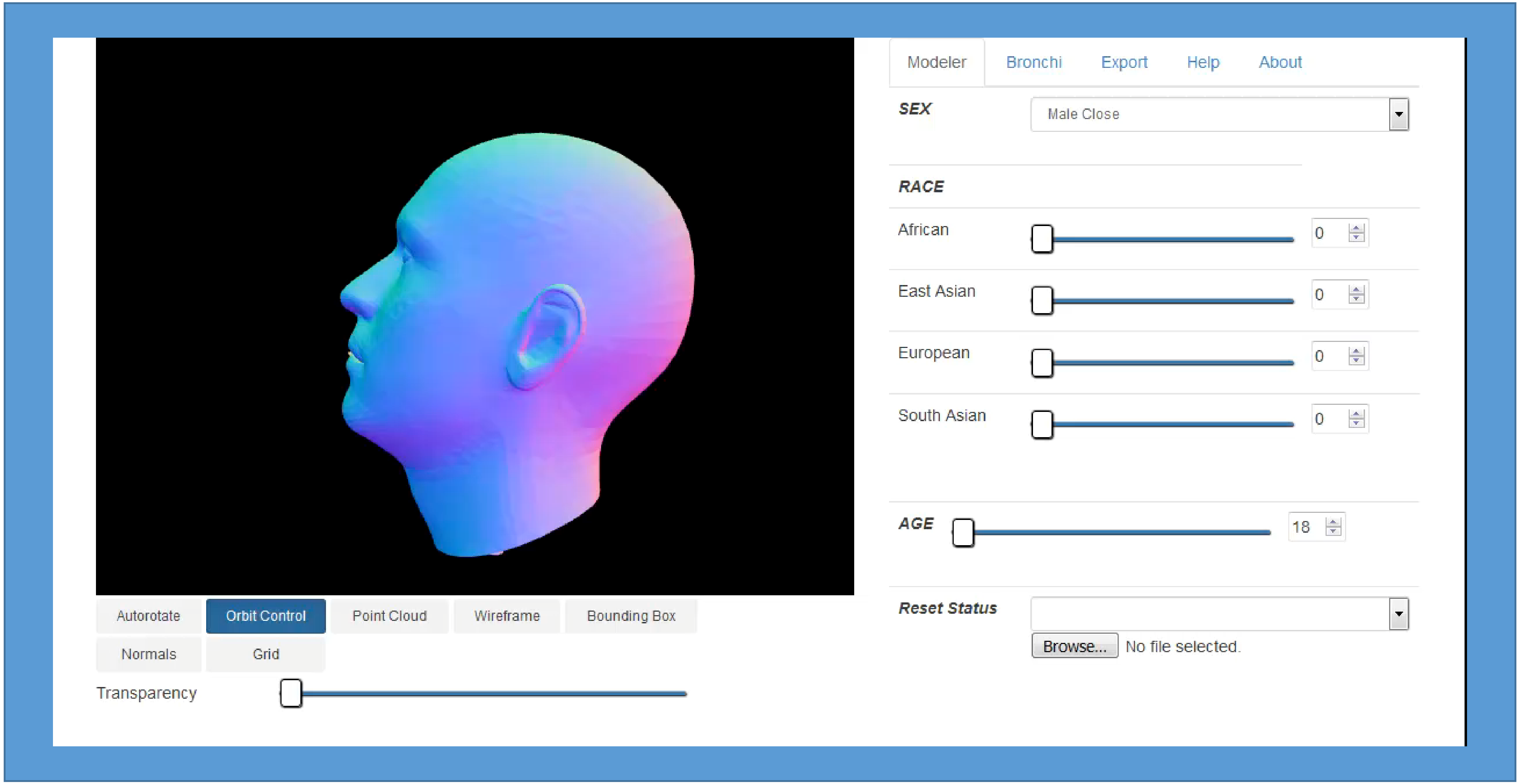
Original Surface Mesh to 10th Generation Created from Stacked CT Images (stacked images courtesy of PNNL)

Centerline and Path Diameter that Matches Original Surface Mesh – Calculated to 23 Generations

New Surface Mesh – to 23 Generations and 5 Lobes (based on centerline and path diameter data)

New Surface Mesh – to 23 Generations and 5 Lobes

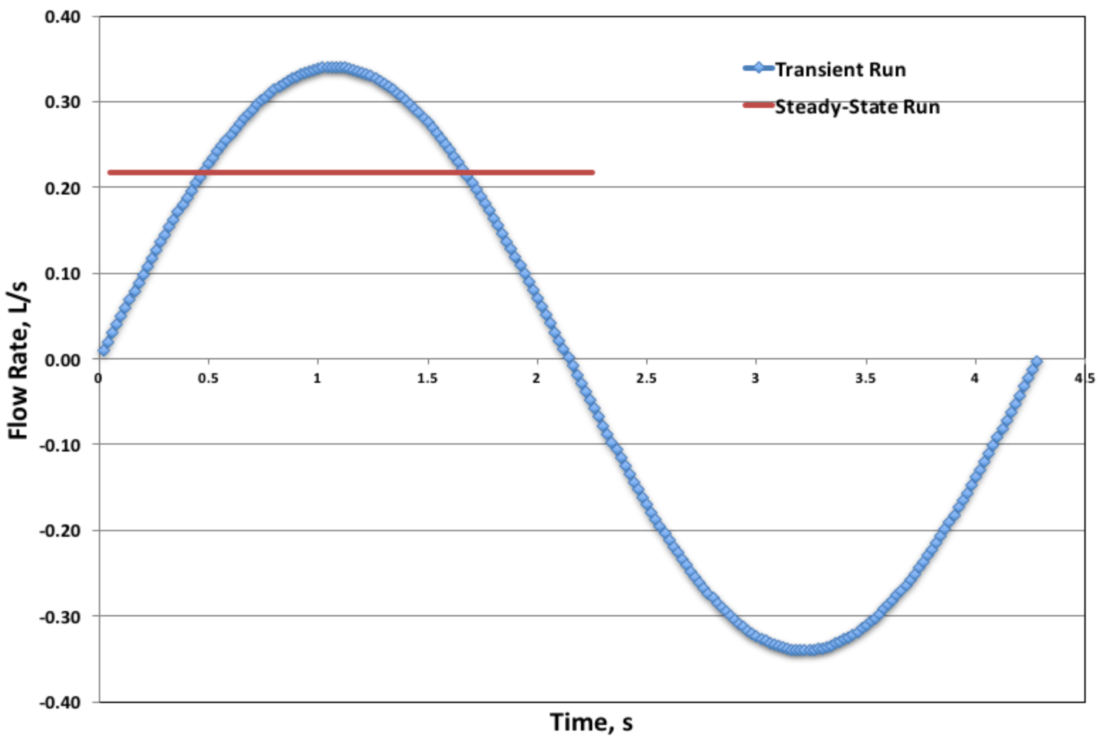
Model Interface



Interface Output – Surface Mesh

- Parameters (age, race, sex, height, weight) are input to the interface.
- Complete surface mesh is generated, from nares to alveolar region, based on these inputs.
- Output is provided in the form of this surface mesh (or complete respiratory system ‘structure’).
- Surface mesh can then be converted to volume mesh and put into a computational fluid dynamics program for flow modeling.

CFD Simulation of a Full Breathing Cycle



Activity level: sitting, rest

Breathing frequency (female): 14 per minute

Ventilation rate: 6.5 L/min

Flow rate changes every time step (0.02s)

Flow during a breathing cycle

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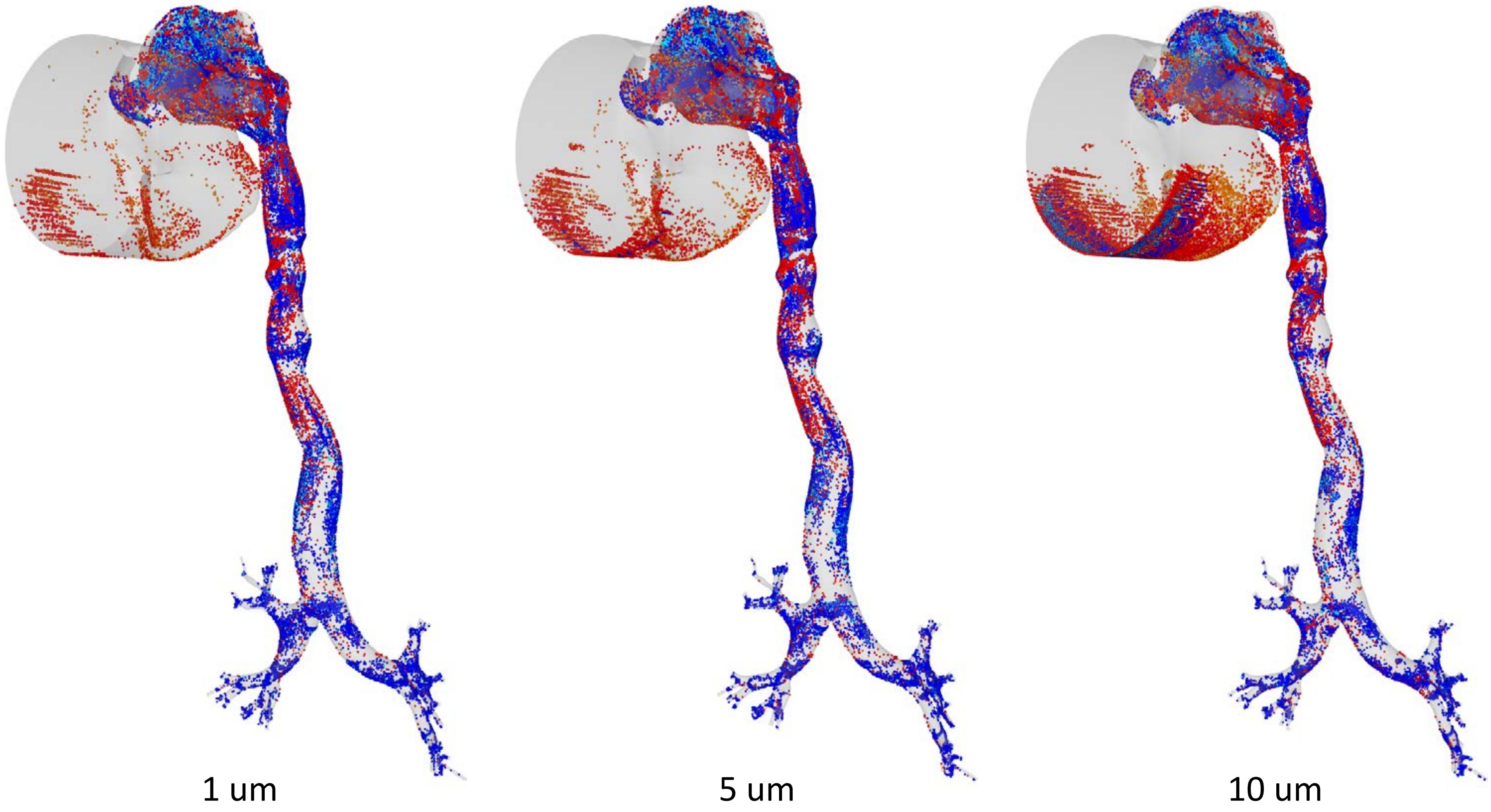
1 um MMAD Particle Tracing – 2nd breathing cycle

(1st breathing cycle used as an initialization stage)

Suspended Particles

Deposited Particles

Deposition on Inhalation (blue) and Exhalation (red)
1, 5 and 10 micron MMAD particles



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Model available for beta testing in early 2018.

The EPA team would like to acknowledge Dr. Rick Corley and PNNL sharing human subject data.

Contact Info:
Dr Jacky Rosati Rowe rosati.jacky@epa.gov