DEVELOPMENT OF A THREE DIMENSIONAL IN SILICO MODEL OF THE HUMAN RESPIRATORY SYSTEM FOR DOSIMETRIC USE

Ray Thomas Burton[2], Jacky A Rosati Rowe1[1]
[1] U.S. EPA, National Homeland Security Research Center, RTP, NC 27711; [2] Lockheed Martin, Research Triangle Park, NC 27711

ABSTRACT

The goal of this work is to create a comprehensive computational, morphologically-realistic model of the human respiratory system that can be used to study the inhalation, deposition, and clearance of contaminants, while making the model adaptable for age, race, sex, and health. Our in silico human respiratory system model, which incorporates the nasal, oral, pharyngeal, and laryngeal passages (extrathoracic region), the trachea and main bronchi (upper airways), the tracheobronchial tree, and branching networks through alveolar region, which allows for nearly any variation of airway geometries and disease status to be studied. The human respiratory system model can be used for studies of sensitive populations and the homeland security community, in cases where inhalation studies on humans cannot be conducted with toxic contaminants of interest.

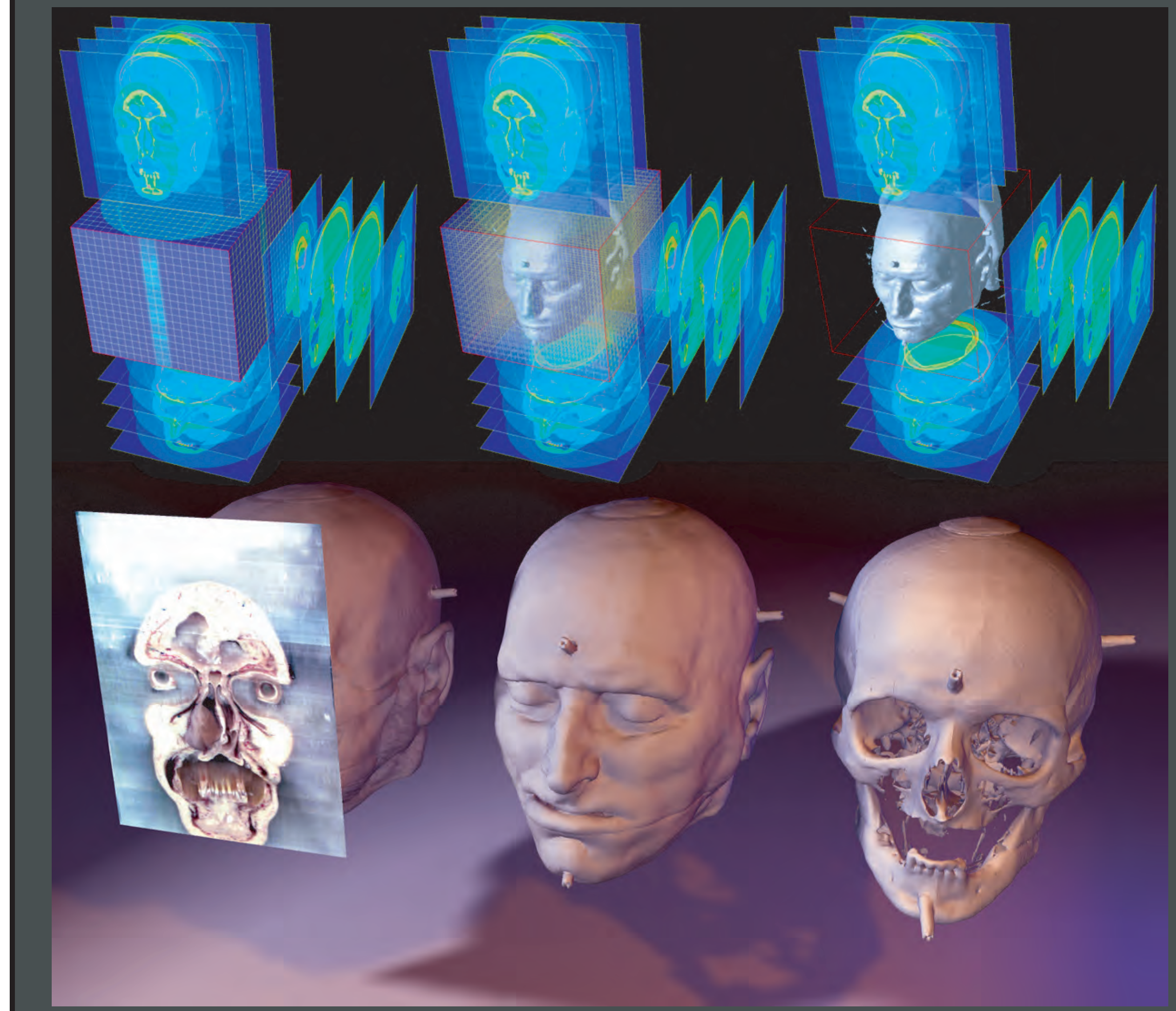
Figure 1 Construction of a volumetric dataset from a series of image slices and initial three-dimensional representation of the underlying soft tissue structure of the human head and the hard bone structure of the skull.

NASAL MORPHOLOGY DEVELOPMENT

The nasal cavity region was extracted from the volume data and isolated. The sinuses were removed from the model to match structures from published literature. Using the nasal isosurface an evenly spaced series of planar curves and points were created from the intersection of a cutting plane through the mesh surface. These contour lines or profile curves were used to fit a new surface through selected profile curves that define the surface shape.

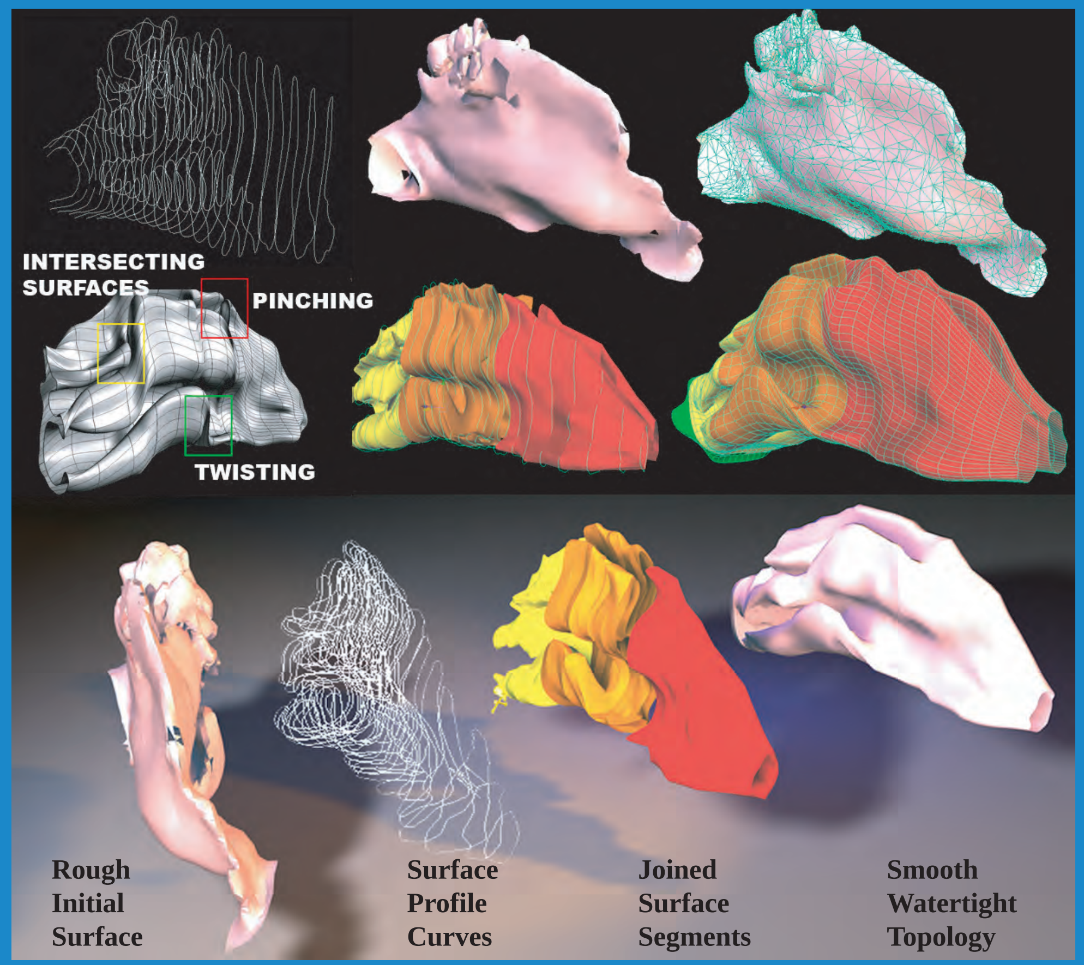

Figure 2 A series of images showing the progression of the nasal cavity model from rough data to rough initial surfacing to joined segments to a final smooth watertight topology.

The nasal cavity was composed of a series of curves obtained from the head data. Contour lines or profile curves were extracted from the nasal cavity mesh obtained via the marching cubes algorithm. These curves are necessary to maintain cohesion to the original mesh and uphold the underlying structure of the turbinates found in all nasal structures. Surface defects occurred during the autosurfacing phase. These anomalies were corrected by auto lofting profile curves with the same curve degree and the same number of edit points into surface segments. The final stitching of the nasal passage surface segments was completed by rebuilding the profile curves, hand manipulating the curve degree and number of edit points on adjacent surfaces segments, and essentially combining two shapes or segments, thereby creating a surface between them.This process formed a closed watertight topology free from intersecting and twisted surfaces (Figure 2).

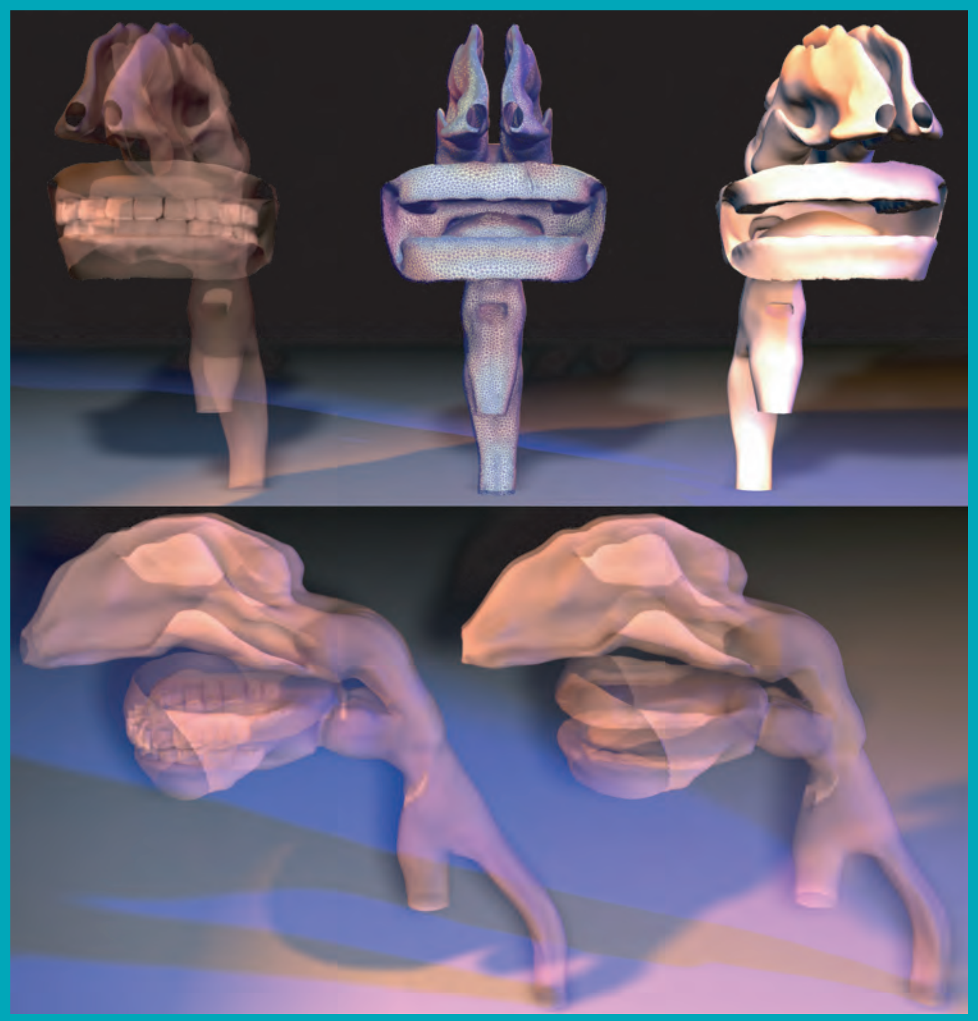
Figure 3 Views of the extrathoracic airways combined with new oral cavity structures detail, complete with teeth, gums, tongue, uvula, and epiglottis.

With a smooth nasal cavity free from defects, the next step was to combine it with the oral cavity. The detail of original oral cavity extracted from the volumetric data was insufficient to be used as a morphologically realistic model. Instead, a dental plate (Digimation dental model VP129) was used as a reference mesh for the teeth with gums. The upper and lower gums and teeth were combined to form a complete oral cavity. A tongue was added and the entire oral cavity was retopologized. The nasal cavity and oral cavity were aligned and combined into a single morphology model, including sides of the oral cavity and uvula (Figure 3). To combine the models effectively, we used merging, sewing, and hole-filling tools that provided flexibility in the joining of the surface segments.

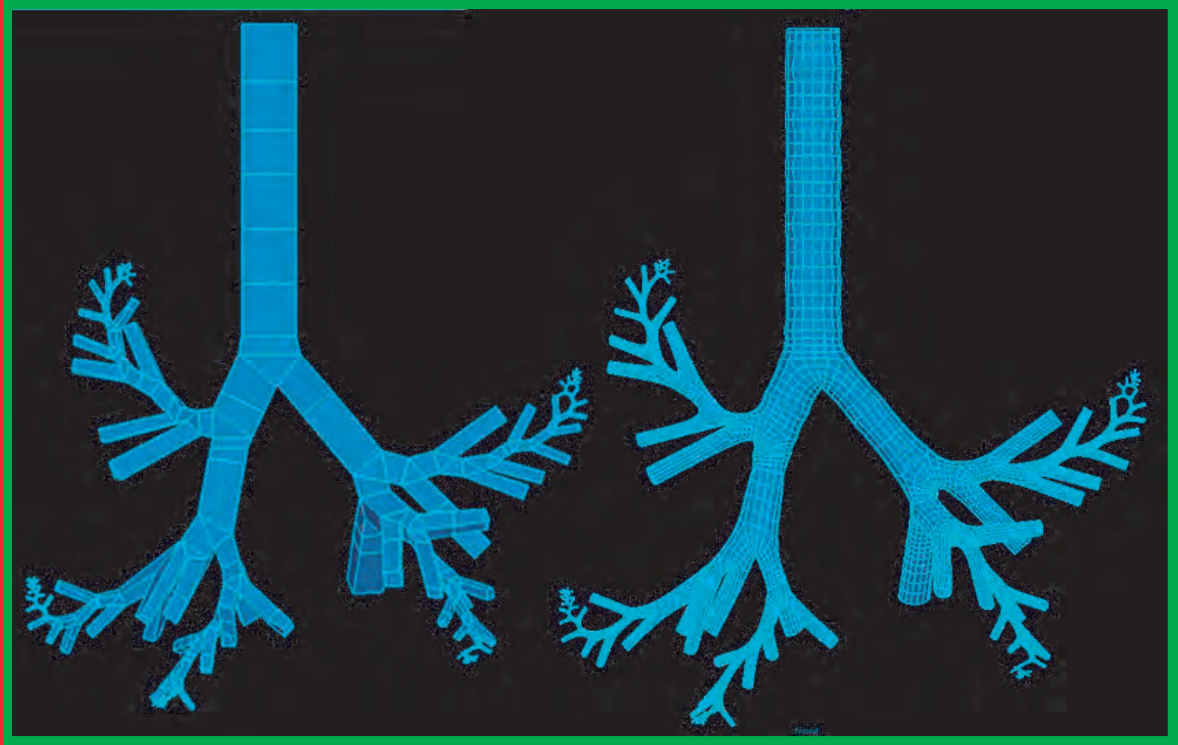
Figure 4 Bifurcation model below the pharynx showing one complete 24 generation path in each of five lobes using the subdivision surfaces modeling method.

AIRWAY DEVELOPMENT

We developed a method of generating a three-dimensional computer morphology model of the human lung branching airway network using subdivision surfaces. A subdivision surface (subdiv) is a method of representing a smooth surface by specifying a coarser piecewise linear polygon mesh. The bottom four vertices of a single polygon cube were selected, scaled, and adjusted to form the bottom apex for the initial triangle that forms all bifurcation intersections in the branching network (generation 1). Each airway is represented by its parameterization into length, diameter, and angles of orientation. The orientation angles consist of the bifurcation angle between two branching airways, and the rotation angle, which is a measure of the rotation of the plane containing the branching airways. After the 24 generations were completed, we applied a smoothing subdivision surface algorithm to generate the final polygon mesh.

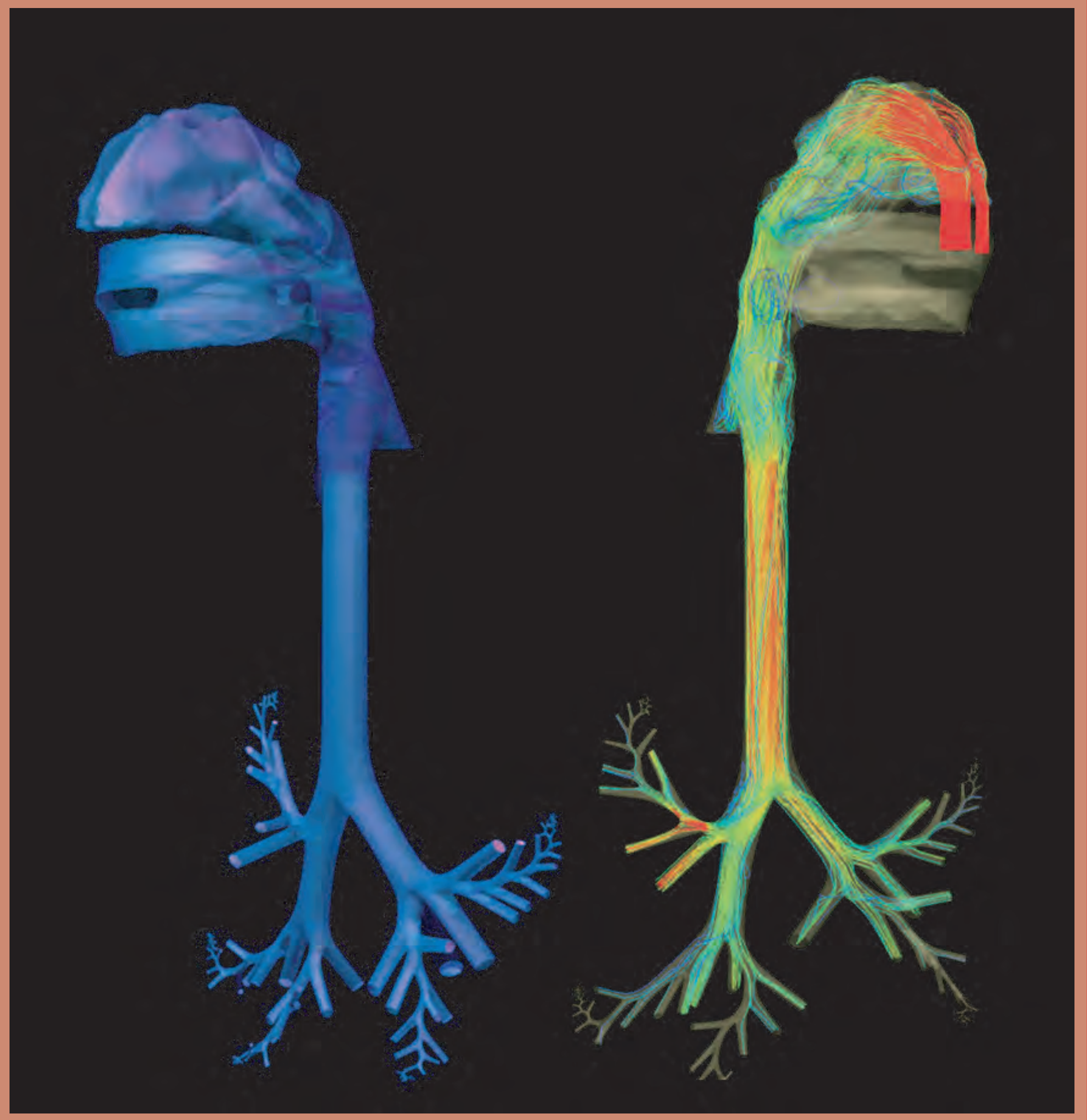
Figure 5 The internal structures were combined to create a three-dimensional morphologically realistic model of the human respiratory tract from the nares to the alveoli (left). To confirm the model was free from surface imperfections we prepared a computational mesh, a process which requires a watertight surface and performed a trial CFD run. Traces of velocity magnitude are shown for inhalation laminar flow (right).

COMPLETING THE INTERNAL STRUCTURES MODEL

The internal structures of a physiologically based nose, larynx, pharynx, mouth, and lung bifurcations were combined to create a three-dimensional morphologically realistic model of the human respiratory tract from the nares to the alveoli (Figure 5). The same method was used as described when combining the extrathoracic models. Briefly, a triangulated mesh was created with surfaces that could be imported directly into computational engineering software for further analysis. A combined model required the use of merging, sewing, and hole-filling tools (provided in the commercial application Rapidform XOR), which allowed for flexibility in joining the separate models (Figure 5).

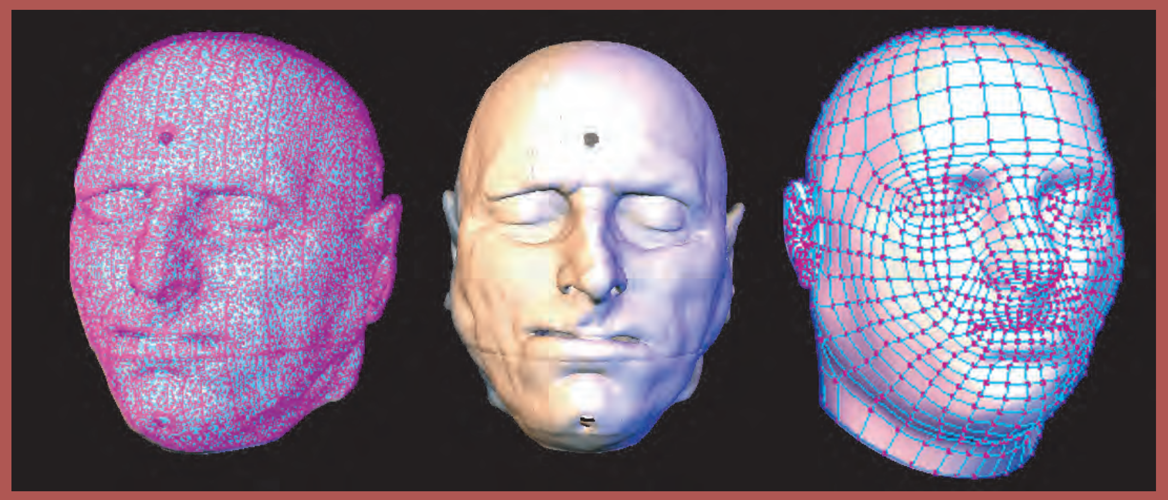
Figure 6 The facial features were retopologized to make the model more suitable to be used as a deformable mesh, that varies by race, gender, and age.

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Embedded Video Player in poster showing the stages in the development of a three dimensional in silico model of the human respiratory system for dosimetric use

EXTERNAL STRUCTURE REBUILD

The original triangulated surface mesh topology, in which each surface element was made up of triangles, was not suitable for deformation because of the highly dense number of surface points (498577 vertices, 1411868 edges and 921622 faces). Using a standalone resurfacing application, TopoGun (PIXELMACHINE SR), the triangulated surface mesh topology was rebuilt to take advantage of a surface constructed with quadrilaterals. Quads surface elements subdivide evenly, which is better for flexible organic models. Also, quads maintain edgeloops; edgeloops are a closed loop of vertices and can be followed around a mesh until they return to their origin" since the subject is edgeloops. Edgeloops allows one to control how the surface bends and folds while the mesh is deformed, morphed, or animated (Figure 6).

The new retopologized head mesh was joined with an idealized external torso, and combined with the internal structure. The nasal and oral cavities were attached to the external nose and mouth by aligning like points on the structures. The model (Figure 7) can respond to the dynamic changes of respiratory mechanics and abnormal pathologies.


Figure 7 Complete contiguous internal and external typical path model, including nasal and oral, cavities, larynx, and 24 generations with a single bifurcating path into each of the five lobes of the lung.

CONCLUSIONS

The human respiratory system model can be used for studies of sensitive populations and the homeland security community, in cases where inhalation studies on humans cannot be conducted with toxic contaminants of interest.

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