Construction of the Human Lung and Air Flow Analysis

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Ventilation within the lung is air shift generated by displacements of intra-pulmonary structures according to the chest motion. In order to study lung anatomy, physiology, and pathology, 4D (=3D + time axis) models are necessary. The present author has developed software for generating 4D lung models from the trachea to alveoli. Since the lung models consist of 4D finite elements, air flow simulation during breathing can be performed by the use of computational fluid dynamics. In this paper, the 4D lung models and airflow analyses within the models are introduced. New respirology based on 4D modeling and simulation is now beginning.

Key words: Airway Tree, Alveoli, Breathing, Computational Fluid Dynamics

1. Introduction

During breathing, respiratory muscles periodically change the chest shape, and the atmospheric air goes into/out the lung. Within the lung, inhaled air is distributed according to periodic change of spatial arrangement of the lung structure. In order to study "intrapulmonary" respiratory physiology and pathology, knowledge of its 4D (=3D + time) structure is necessary. The present author previously proposed four algorithms which construct geometric models of 3D airway tree (Kitaoka *et al.*, 1999), 3D pulmonary acinus (Kitaoka *et al.*, 2000), 4D alveolar system (Kitaoka *et al.*, 2007), and 4D lung shape (Kitaoka and Kawase, 2007).

Recently, software generating 4D lung models from the trachea to alveoli has been developed by integrating those four algorithms (Kitaoka, 2011). The application software can be freely downloaded from a personal homepage of the present author (http://www7b.biglobe.ne.jp/~lung4cer). Since the lung models consist of 4D finite elements, air flow simulation during breathing can be performed by the use of computational fluid dynamics (CFD).

2. Airway Tree

The human airway tree begins from the trachea beneath the vocal cords and goes down to the chest. It bifurcates into bilateral main bronchi, and finally generates nearly a million bronchioles with diameter of 0.4 mm after branching about twenty times (Weibel, 1964). Since the airway looks like a tree, it is called the airway tree.

The central thick airway is assigned beforehand so as to meet common findings in the textbook of anatomy. Other parts are automatically generated according to the algorithm (Kitaoka *et al.*, 1999). Colors in peripheral bronchi indicate anatomical classifications for the lung regions.

Figures 1 and 2 show a human airway tree model consisting of about 40,000 branches. Self-similar branching patterns are realized down to terminals. The surface of the tree model is a connection of numerous triangle units.

Figure 3 indicates inside views of the airway tree model, corresponding to clinical bronchoscopic images. Let us go to the branch (the anterior basal bronchus in the right lower lung lobe) in the left lower part in the leftmost shot in Fig. 2. First, enter from the open end of the trachea (left upper shot in Fig. 3), and go right and downwards. Then, we can slightly see three orifices (light spots in the left lower shot). Go ahead a little through one of these orfices, and you can see the whole orifice of the bronchus with next branching. (right lower shot).

Figure 4 indicates sliced images of the airway tree corresponding to clinical CT images, though real CT images are gray-scaled. The three shots (left upper and lower, right upper) are images at the same position, while the right lower one is a five-time magnified image of the right upper image. Note that different slice thickness generates different configurations, so that the five-time magnified image with 2 mm thickness is similar to the image with 10 mm thickness.

3. Alveolar System in the Human Lung

The airway tree described in the previous section is distributed everywhere in the lung. However, its volume is only less than 10%. The remaining 90% is the volume of the alveolar system consisting of alveolar ducts. The alveolar duct is a space-filling and branching air pathway surrounded by alveoli.

Ends of the airway tree are respiratory bronchioles, which connect to alveolar ducts. The alveolar system supplied air by the last respiratory bronchiole is called subacinus.

Figure 5 shows an example of air pathway from the trachea to a subacinus (left two shots). In this pathway, an alveolar duct appears after 19-time branchings from the trachea, and conveys air to 1,200 alveoli. There are many

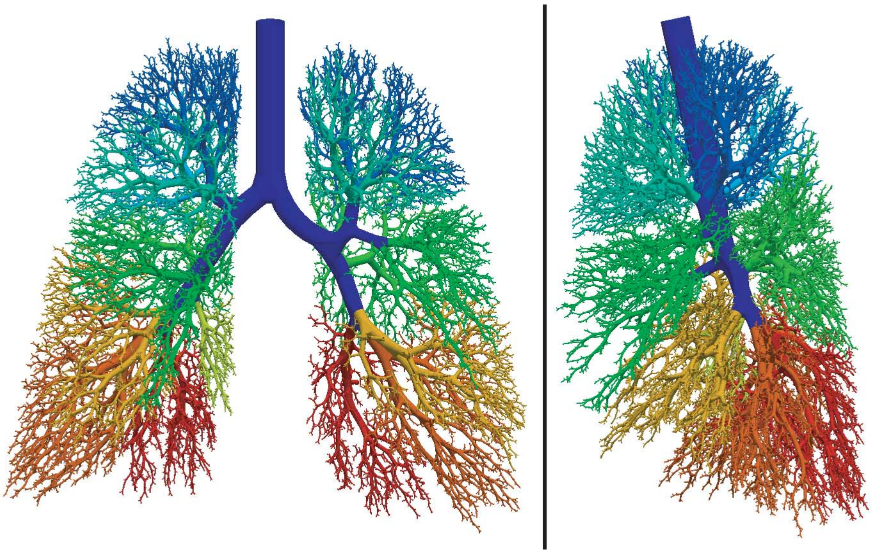

Fig. 1. Human airway tree model.

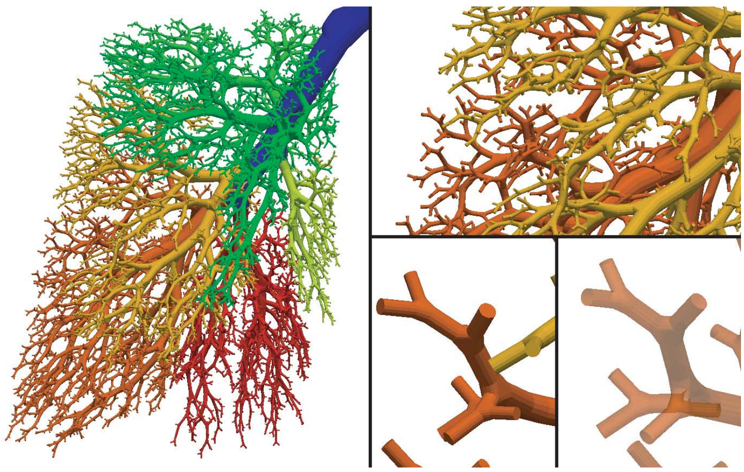

Fig. 2. Magnified pictures of the human airway tree model.

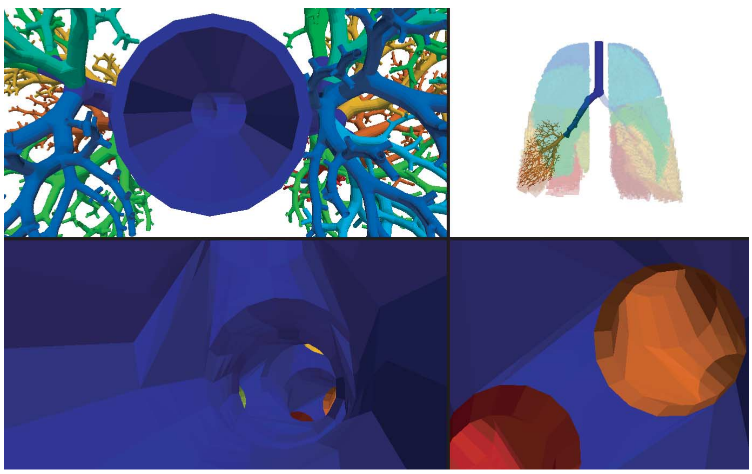

Fig. 3. Virtual bronchoscopic images.

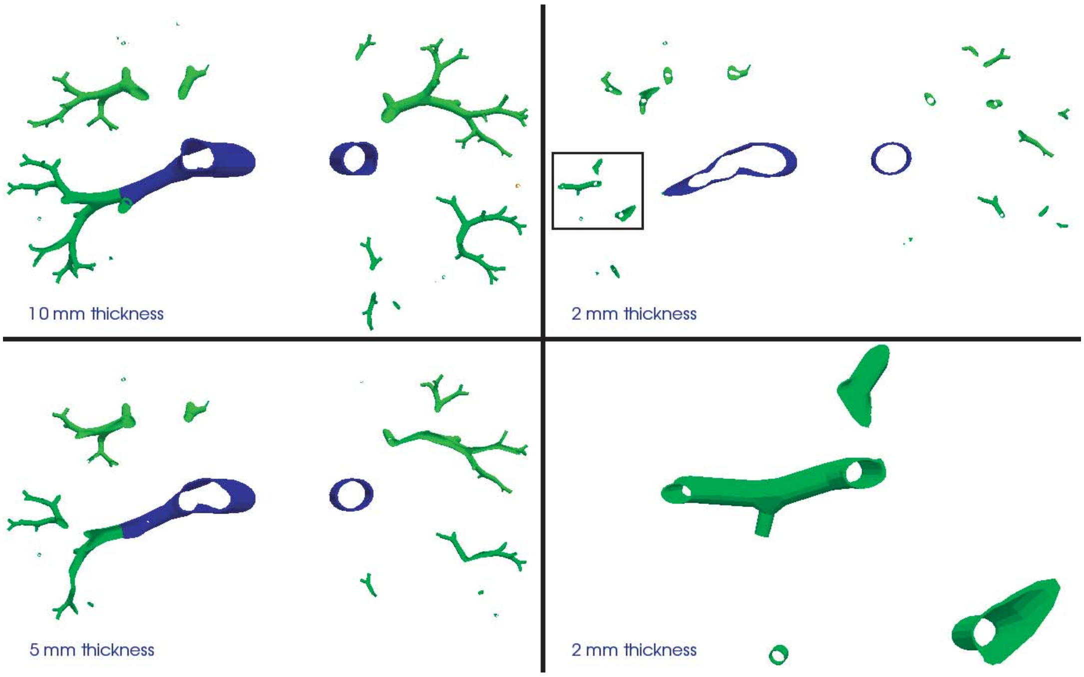

Fig. 4. Virtual CT images.

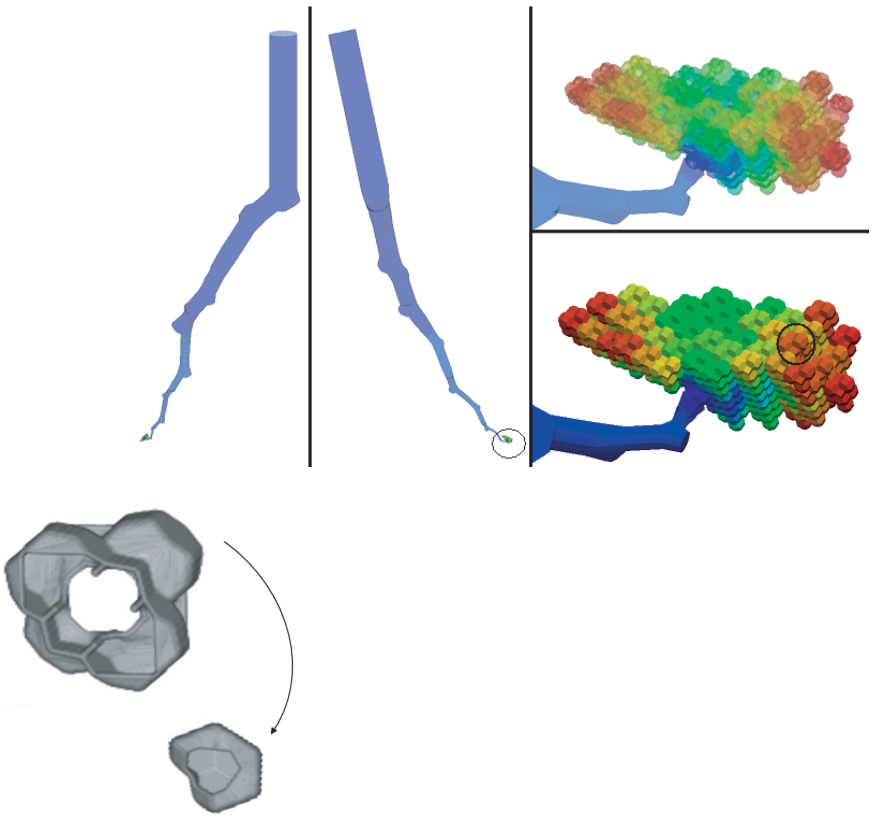

Fig. 5. Air pathway model from the trachea to alveoli.

bumps on the surface of the subacnus (middle shots, upper: semi-lucent, lower: opaque). Those bumps are all alveoli. The right shots in Fig. 5 indicate a part of the alveolar duct marked by a black circle in the middle lower shot. Inside view of the alveolus is indicated in the right lower shot.

Kitaoka's alveolar duct model (Kitaoka *et al.*, 2007) is a 4D model including breathing motion. When the air is inspired, alveolar mouths are widely opened and the duct volume increases (Fig. 6). When the air is expired down to the deepest level, alveolar mouths are closed. Figure 7 indicates real rat alveolar ducts in comparison with the virtual model produced by the Kitaoka's algorithms. Small

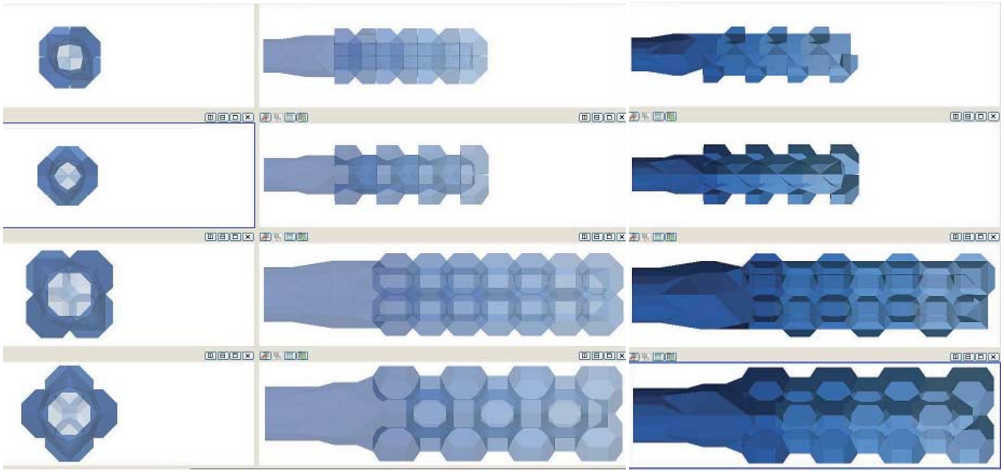

Fig. 6. Deformation of the alveolar duct model during breathing. Upper two rows: at full expiration. Lower two rows: at full inspiration. Left: longitudinal direction, Middle: radial direction, Right: cut surface.

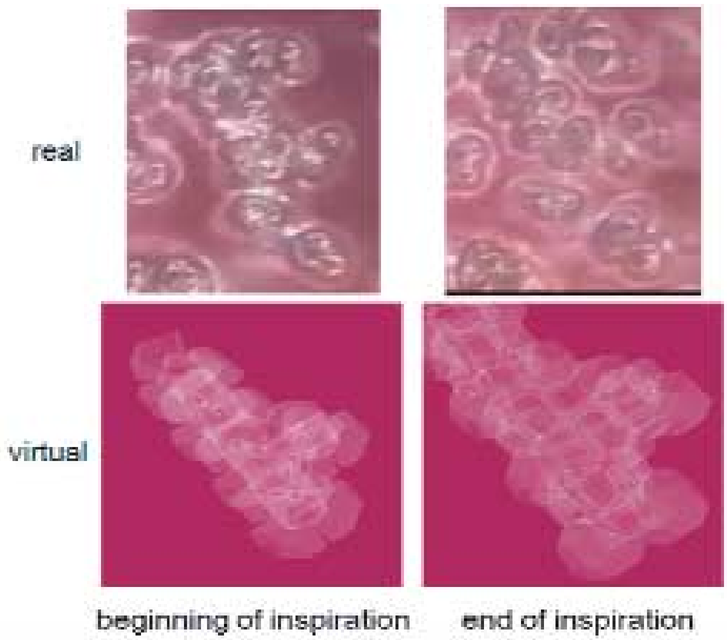

Fig. 7. Breathing motion of alveolar ducts, real vs. virtual model.

white rings at the centers of rat alveoli are alveolar mouths. The rat lung was treated in a special manner in order that respective alveoli could be observed. Figure 8 indicates real specimens of the human lungs in comparison with the virtual model. Red arrows in Fig. 8 indicate branching spurs of alveolar duct.

4. Analysis of air Flows during Breathing

Ventilation within the lung is the air shift generated by displacements of intra-pulmonary structures according to the chest motion. Therefore, a 4D lung model enables us to simulate airflow in the lung during breathing by solving Navier-Stokes equation under moving boundary conditions. However, it is necessary for CFD (Computational Fluid Mechanics) to convert a lung model from merely geometric one into FE (Finite Element) mesh. In this section, 4D-FE lung models and airflow simulations with the FE models are introduced (CFD solver: AcuSolve, Altair Engineering Co., USA).

4.1 Airflow within the alveolar duct

An alveolar duct model with two duct units indicated in Fig. 9 was applied. The longitudinal length is 1.0 mm at the end of inspiration. Airflow during deep inspiration (4 sec) and expiration (6 sec) were simulated with time step of 0.1 sec. Figure 10 visualizes computed airflow with trajectories of massless tracer particles placed at the open end of the alveolar duct at the beginning of inspiration. During inspiration, the air goes into insides of alveoli through enlarged alveolar mouths. During expiration, the air goes out of the alveoli through the alveolar mouth.

4.2 Intra-subacinar airflow

Figure 11 indicates airflow during inspiration within an acinar model containing 100 alveoli. Massless particles placed along a longitudinal line at the center of the subaci-

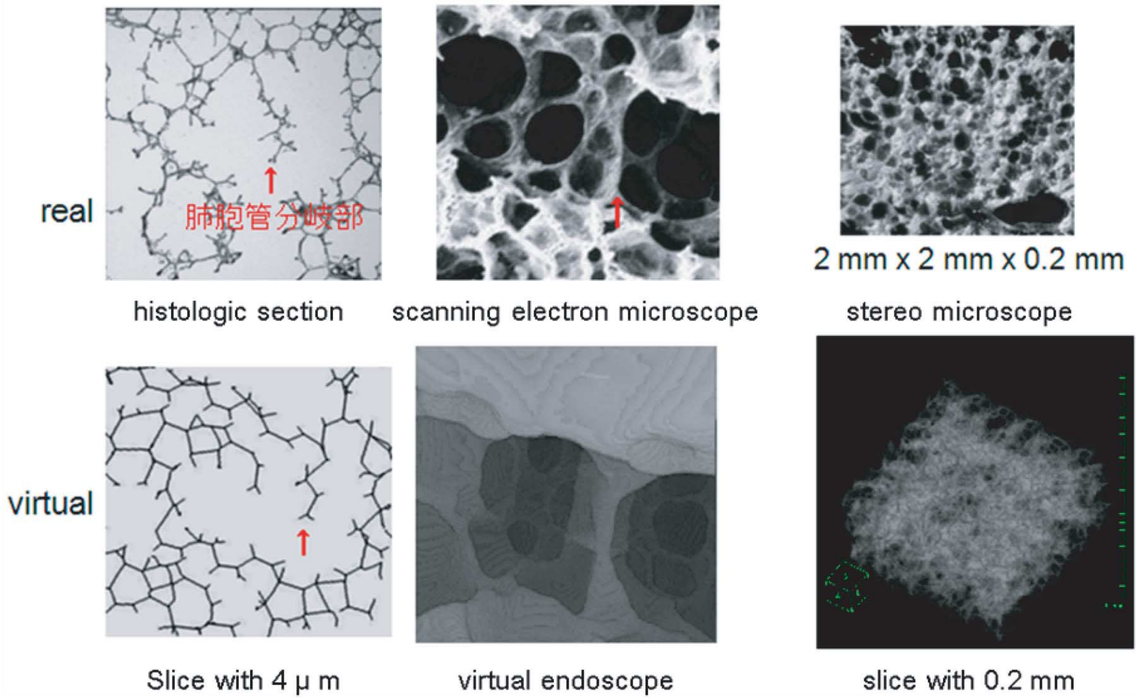

Fig. 8. 3D structure of the alveolar system, real vs. virtual models.

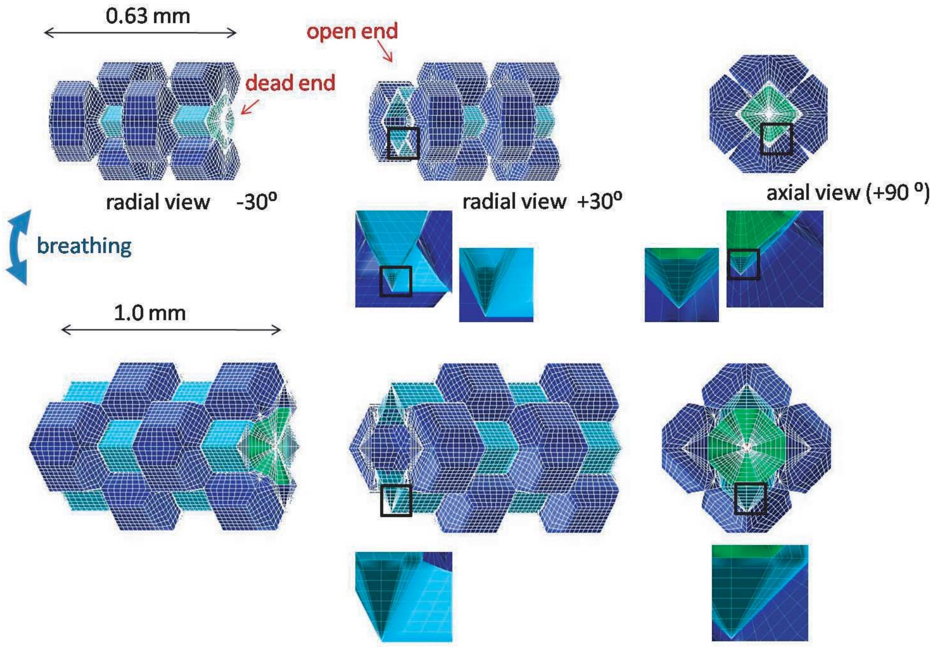

Fig. 9. 4D finite element model of the alveolar duct.

nus are spread within the subacinus forming a complicated pattern.

4.3 Intra-tracheal airflow

Pulmonary emphysema, over-inflation of the lung, causes chronic severe respiratory failure. Wheezes, the most common adventitious lung sounds in pulmonary emphysema, are continuous musical sounds during expiration with the duration of more than 250 ms and a dominant frequency of 400 Hz or more (Meisner, 1995). Although the textbook tells us that wheezes are generated in small airways, tracheal deformation during forced expiration is thought to be the most probable cause, if effects of fluid dynamics are taken into account. Figure 12 indicates pressure fluctuation with the frequency of 600 Hz due to periodic vortex generation at a deformed tracheal wall (time step = 0.0001 sec).

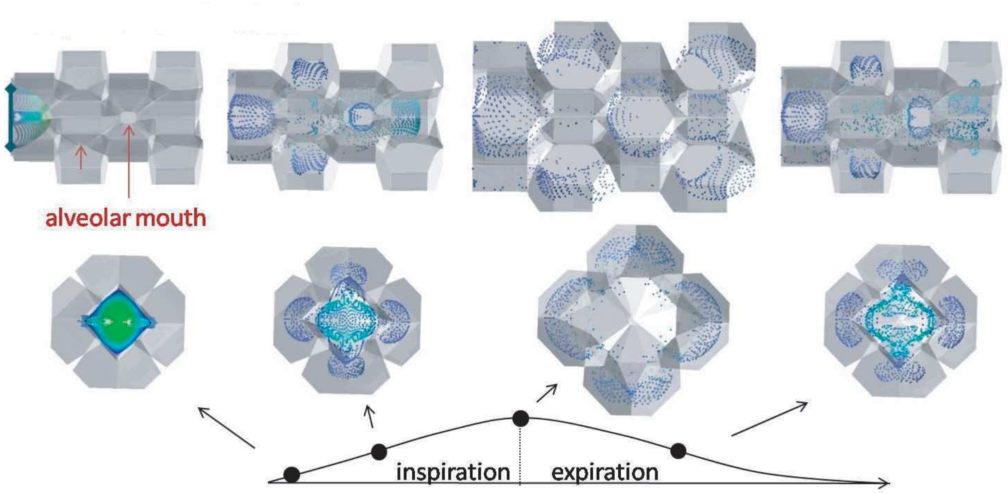

Fig. 10. Massless particle tracing during one cycle of breathing.

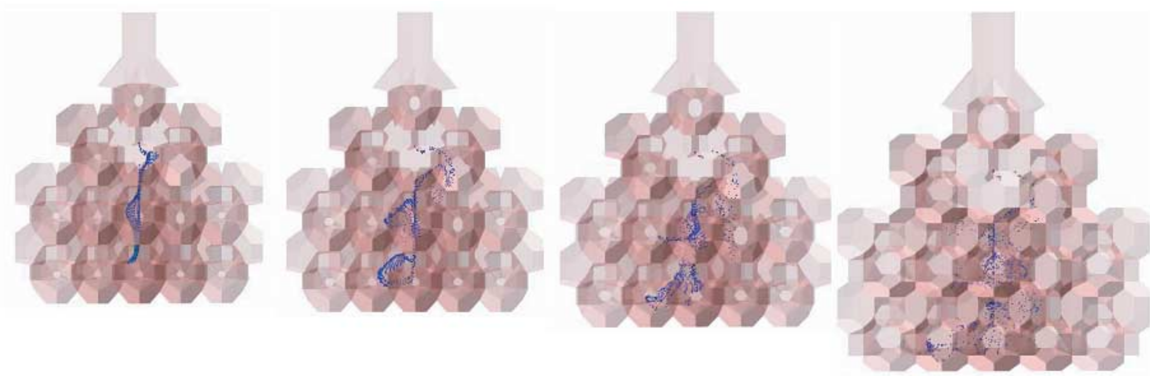

Fig. 11. Trajectories of massless particles within an acinar model.

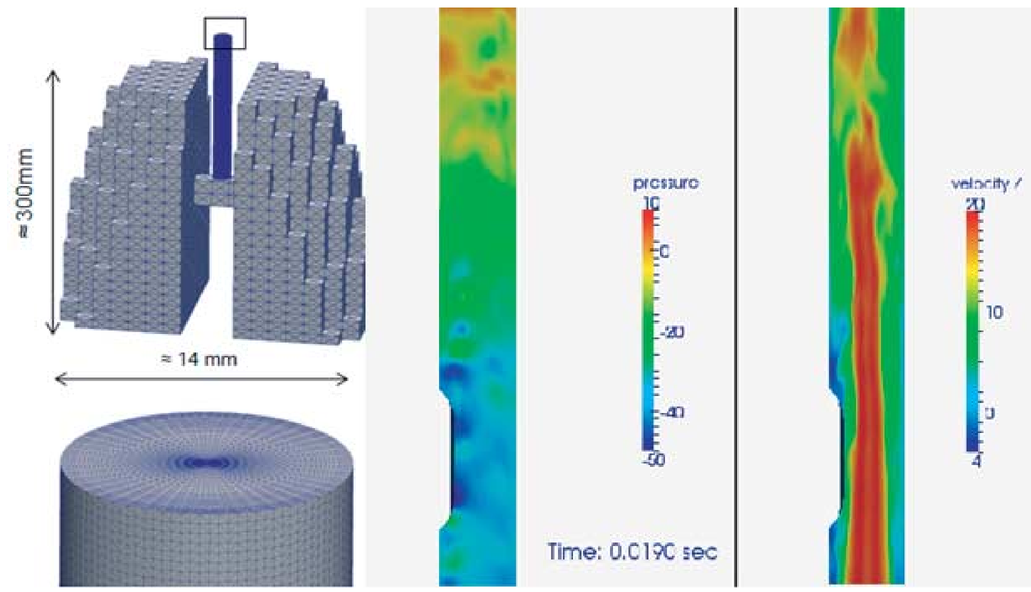

Fig. 12. Tracheal FE model connected to the lung (left) and simulated airflow (right).

5. Concluding Remarks

In this review paper, dynamic 3D lung models from the trachea to alveoli and airflow analyses by the use computational fluid dynamics were introduced, which are mostly developed by the present auher. New respirology based on 4D modeling and simulation, as explained in this paper is now beginning.

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