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EXAMINATION OF THE BASIC GEOMETRICAL PARAMETERS OF THE LOWER RESPIRATORY TRACT OF THE HUMAN AND ITS SIMPLIFIED COMPUTATIONAL MODEL

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Abstract: *This contribution deals with the examination of the basic parameters of the lower respiratory tract of a human. Among these parameters are the diameters (cross-section area) of the channels dependent on the remoteness from the Larynx, the length of the individual branches, angles etc. Further we propose a semi-automatic method to regenerate the simplified geometry of the lower respiratory tract of a human from very detailed input (described by a surface mesh) for the subsequent formation of a 3D computational model. The final simplified geometry can be adjusted by user intervention (e.g. changing the specific diameter). The key feature in the simplification is that the cross section areas and channel length of the lower respiratory tract are maintained. The final 3D computation model of lower respiratory tract is easy to connect with a simplified vocal tract model (Vampola et al., 2008) and the basic acoustic characteristic or fluid flow depends on the tract geometry may be examined.*

Keywords: Lower respiratory tract, Human lung parameters, Computational model, Trachea, Mainstem bronchus.

1. Introduction

The lungs are the primary organs of respiratory and they are situated within the thoracic cavity of the chest. Human lungs are split to the two parts – the left and right lungs. The right lung is bigger that the left, because the left lung shares more space in the chest with the heart. The main parts of the right lung are called the right lower, the middle and the upper lobes of the lung. The left lung has 3 parts too. They are called the left lower and the upper lobes of the lung and the Lingula.

Fig. 1: Detail (cross-section) of surface mesh obtained by MRI.

The lower respiratory tract begins at the trachea and branches into the bronchi and bronchioles which receive air breathed in via the conducting zone. These divide until air reaches microscopic alveoli, where the process of gas exchange takes place.

The primary function of the lung is breathing, but the main cavity of the lower respiratory tract (e.g. Trachea) is connected with the vocal tract and together form the phonation space.

This paper describes the formation of a simplified computational model of the human lower respiratory tract, which come out from the geometry obtained by magnetic resonance imaging (MRI).

The base of our model is a triangular surface mesh, which contains all right and left lobes, Trachea, Primary and Secondary bronchi and several other levels of branching (Fig. 1). A certain publication (e.g.

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Rozanek et al.) presents, that branching inside human lungs is occurs up to the 23rd level. In view of the fact that the resolution of the scanner and following reconstruction of the surface mesh for our model contains just several first levels (until diameters of 1 mm, it corresponds with the 9th – 11th levels of branching).

The quality of the surface mesh is not sufficient for directly forming the computational model, because it contains a lot of poor quality elements. The channels of smaller diameters are formed by large surface elements (probably due to points set reconstruction) and a very small number, which greatly distort the real geometry of the channels (see Fig. 2). This surface mesh is also called "dead", which is very difficult to modify (only by manual intervention).

Our goal is to map the basic geometrical parameters (cross-section area, length of individual branches, etc.) and form the computational model, which will be simply modifiable and is based on the real geometry. It allows to simply simulate various pathological phenomena and detect their influence on the quality of the human voice.

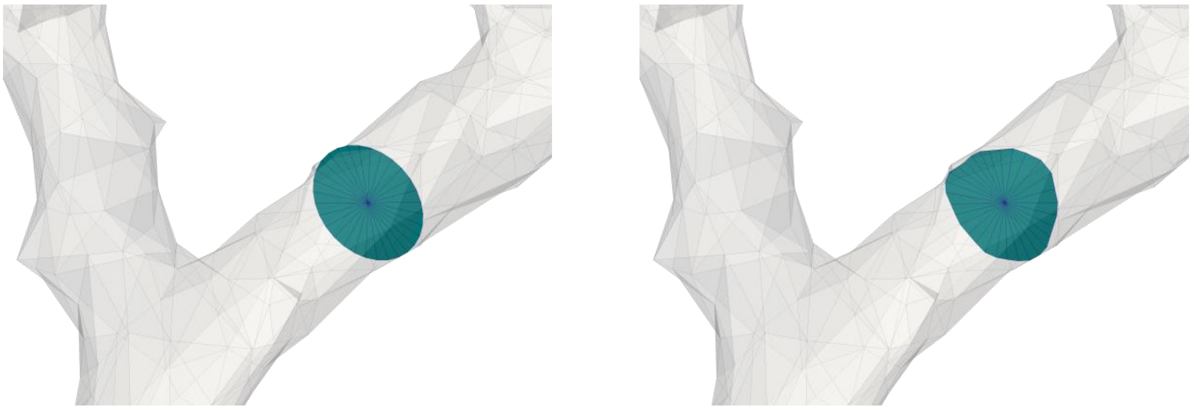

Fig. 2: Poor quality of the surface (remoteness from Larynx 230 mm).
Comparison of reconstruction cross-section area (left) and original shape (right).

2. Mapping of basic parameters of the respiratory tract

For forming a computational model which faithfully describes the real geometry a thorough mapping of the basic parameters for the available surface mesh of the respiratory tract is necessary.

2.1. Cross – Section Area reconstruction

The first parameter (from which another can be found) is the minimal cross-section area of channel according to the remoteness. The minimal value of the area indicated, that the cross-section is perpendicular to the centerline of the channel. Our approach for minimal area searching inside the channel is based on the optimization process. A target function is the minimization of the cross-section area specified with number of triangles (see Fig. 2). The normal vector for each triangle can be determined by (5), where matrix (1) - (3) are the basic transformation matrix for rotation motion (Valášek et al., 2004). Optimization parameters for the cross-section minimization are 3 angles (α, β and γ). The optimization process is controlled by the Octave software (Eaton et al., 2009) using the optimization toolbox.

$$T_{\varphi x}(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) & 0 \\ 0 & \sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (1) \qquad T_{\varphi y}(\beta) = \begin{bmatrix} \cos(\beta) & 0 & \sin(\beta) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\beta) & 0 & \cos(\beta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$T_{\varphi z}(\gamma) = \begin{bmatrix} \cos(\gamma) & -\sin(\gamma) & 0 & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3) \quad r = T_{\varphi x}(\alpha) T_{\varphi y}(\beta) T_{\varphi z}(\gamma) \begin{bmatrix} 0 \\ 0 \\ 1 \\ 1 \end{bmatrix} \quad (4) \qquad n = \begin{bmatrix} r(1) \\ r(2) \\ r(3) \end{bmatrix} \quad (5)$$

2.2. Centerline of the channel

One of the basic parameters of the complex branching channels are so called centerlines of the channel, which describes the channel direction, diameter of the placed sphere inside a channel and the distance from entry into channel (in our case the Larynx). The centerline can be found as the gradual connection of the closest centers of gravity for a cross-sections from section 2.1. Searching for the minimal cross-section area inside the channel forming a centerline can be done in one step. Just enter the start and final point and the optimization algorithm will complete the whole journey. A flowchart of the centerline searching process is shown in Fig. 3. The new current point of the centerline is dependent on the surface normal – during the optimization process a turn off from the normal can happen and the next current point is the one that is the closest to the final (target) point.

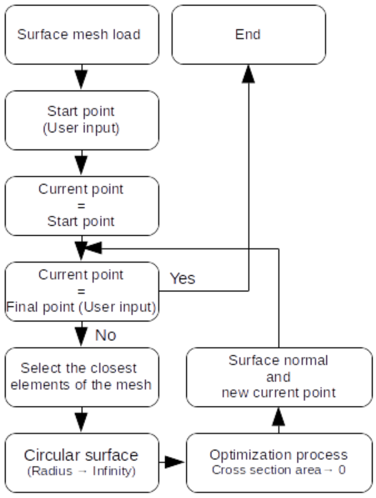

Fig. 3: Flowchart of optimization process.

2.3. Equivalent diameter

For forming of the simplified computational model, it is advantageous to replace the real cross-section of the channel with a regular shape, e.g. circular or elliptical section. In our case is we used a circular section, because it is close to the real shape, see Fig. 2. The regular shape is easy to parametrize for the easier formation of the computational model, as shown in section 2.4.

Dependence of the equivalent diameter of the channel to the remoteness from larynx is shown in Fig. 4. The graph shows, that equivalent diameter increases at the points of branching. The graph records the path from Larynx (0 mm) over the Trachea (0 – 100 mm), Left Main bronchus (100 – 150 mm), Left Upper Lobe Bronchus (150 – 200 mm) to the Tertiary Bronchi (black highlight area in Fig. 5 left).

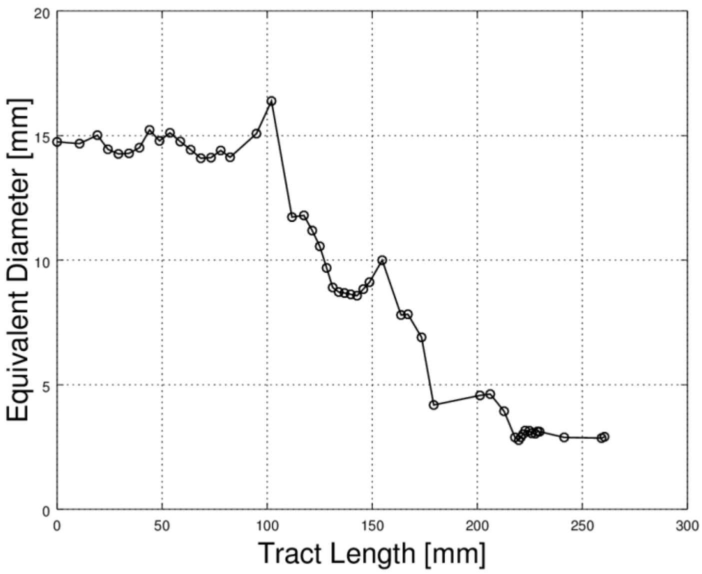

Fig. 4: Equivalent diameter for the investigated part of the channel

3. Forming of the 3D computational model

By careful examination of the geometry of the lower respiratory tract, it is obvious that even in these complex branching channels only 2 basic elements occur – straight parts and branching parts. This fact can be very helpful for the semi - automatic forming of the computational model. Also, for forming the 3D finite element model, both basic element (straight and branched) can be parametrized and produce the computation mesh based on hexahedrons elements (or only 2D elements), as shown in Fig. 5 on the right. The parameters are input diameters, normal of the cross-section area (from section 2.1.), branch lengths but also the number of elements (including boundary layer). One possibility is to use meshing free software GMSH (Geuzaine et al., 2009) which comprises own scripting language. The Fig. 5 right shows a geometry deviation of the reconstruction mesh (blue elements) and surface mesh obtained by MRI (grey surface).

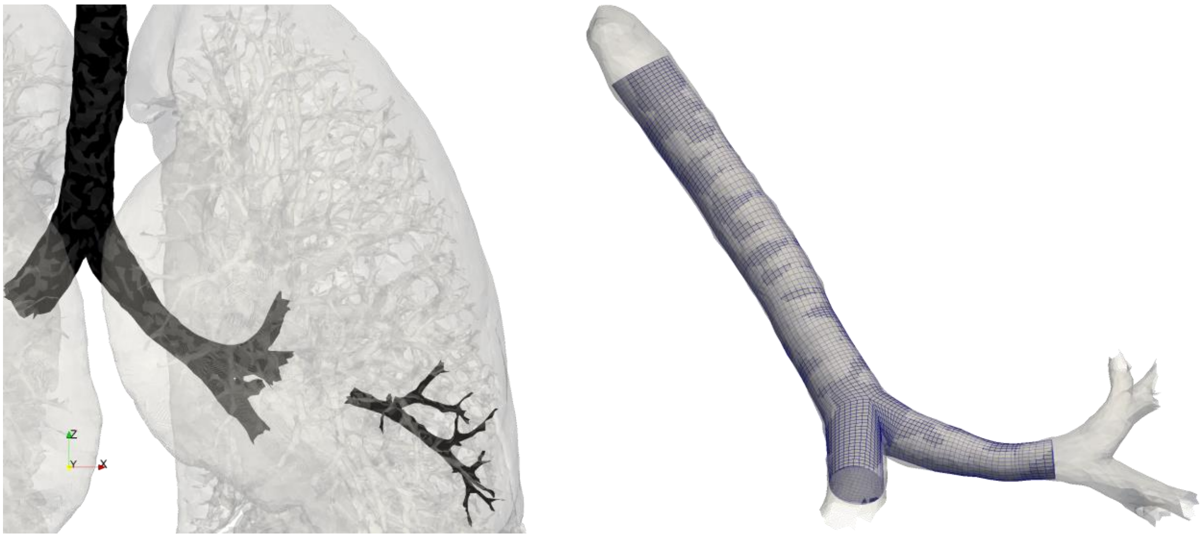

Fig. 5: Highlight of modeled parts (left) and 3D computational mesh of Trachea and left Main Bronchus (right).

4. Conclusions

This paper introduces the basic procedure for forming the computational model of the complex branching channel, which can be used as an input for the finite element method (FEM), and also the finite volume method (FVM). The model is based on the known surface mesh, which is inappropriate for directly creating the computational model (poor quality elements, impossible parametrization). The model is formed by the help of two basic construction elements (straight and branched part), which are gradually linked to the one whole. Both constructions elements are fully parametric (geometry and mesh) and are formed by the scripting language of the GMSH software (Geuzaine et al., 2009) and controlled by Octave (Eaton et al., 2009). Therefore it is possible to simply edit the model geometry and create a computation model for various pathologies.

Acknowledgement

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