Solid-state Modeling of Human Tracheobronchial Tree for 23 Generations of Airways

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Abstract. A three-dimensional solid-state model of the human tracheobronchial tree for 23 generations of airways is constructed in this work, using a specialized software package SolidWorks. It is shown that with a significant increase in computational resources, the model obtained can be applied for computational experiments.

1. Introduction

To study the aspects of flow and transport of particles in lungs, and to increase effectiveness of medicinal aerosol preparations, it is necessary to understand the mechanisms of the air flow behavior and the transfer of aerosols in the airways. To determine the spatial geometry of the air flow region, and to study the displacement of air particles or aerosols in the lung, three-dimensional solid-state models of human tracheobronchial tree (TBT) are used. They provide three-dimensional visualization and can serve as a basis for modeling in computational fluid dynamics. Human TBT is a complex asymmetric structure of gradually branching airways. The trachea is divided into two main bronchi entering the right and left lungs (Figure 1), which, when entering the lung, are called "stem" (first order). Further, in the lungs, the main bronchi continue to divide and branch into smaller bronchi, and the latter divide into bronchioles. As branching from the trachea to the periphery, the diameter and length of subsequent generations of airways decrease, and the total area of their cross section increases in the same direction due to an increase in the number of the latter in more distant generations [1, 2, 3, 4, 5].

Figure 1. Branching generation of the airways [1]
According to the TBT morphometry proposed by Weibel [2], there are 23 generations of airways, along the airway of the human lungs, the first 16 of which are known as conducting and refer to an anatomical dead space. Bronchioles of the 17th and 19th generation belong to the transition zone, in which there is a slight gas exchange. Bronchioles of the 20-23 generations belong to the respiratory zone and form the parenchyma of the lungs [2, 3]. In the 23rd generation there are 8388608 pairs of airways [2], so even the construction of a solid-state model, not to mention numerical calculations, requires huge computing resources that far exceed the capabilities available on powerful personal computers. Therefore, at the moment only simplified partial models of the TBT are used and there are no complete TBT models for all 23 generations.

The purpose of this paper was to investigate the possibility of constructing a solid-state model of human TBT for all 23 generations of airways. To achieve that the task was set: to try to build the model to the extent that it is possible.

2. Methods
Currently, the intensively developing direction of studying the biomechanics of the respiratory system is computer simulation. Thanks to modern integrated systems of geometric modeling and analysis, such as SolidWorks and ANSYS, you can create not only virtual images of models, but also explore them with the help of modern tools of engineering computer analysis. In this paper, construction of a three-dimensional model of TBT was carried out in the automated design system Solid Works, intended for solid-state parametric modeling on personal computers. Application of the specialized software package ANSYS is also allowable, but on the computer that was available to the author the system did not allow to save the model in the same (as much as possible) volume as in the SolidWorks software package, so for the final version of the simulation was chosen the latter package.

3. Results
According to Weibel’s morphometric model [2], TBT can be represented as a symmetrical system of branching tubes with regular dichotomy and fixed length with respect to the diameter of the airways (Figure 2). The model proposed by him was developed on the basis of data from a study of prepared healthy lungs and bronchograms of living people, analyzed using statistical methods [2, 3].

For ease modeling, the following assumptions were made [2]:
• lungs are a set of generations of airways (channels) located parallel to each other. Each "parent" airway gives rise to two "child" branches;
• airways branch out according to the type of regular dichotomy, that is, two conjugated elements have the same dimensions and branch off from their "parent" at equal angles;
• the pressure in the respiratory structure is evenly distributed along the length of each individual air unit;
• airway elements are in the form of a hollow cylinder, two ends of which are cut to the wedge shape, in order to allow stitching with other elements during modeling. At the proximal end, it is conjugated to the "parent" airway, and at the peripheral end to the "daughter" branches.

![Figure 2. The symmetrical model of Weibel's TBT for the first four generations [2, 3]](image-url)
The maximum possible solid-state model of human TBT for 23 generations of airways (the trachea is taken as zero generation) with the regular dichotomy (Figure 3) was constructed using a specialized software package SolidWorks. To simulate the geometric image, we used the quantitative characteristics given in Weibel's paper [2] (Table 1). The angle of bifurcation is the angle at which the "daughter" airways, formed by their axes with the "parent" axis, diverge - in this work was assumed equal to 65° [4].

Table 1. Dimensions of human airways with regular dichotomy [2]

| Generation | Number per generation | Diameter d(z) | Length l(z) | Total crossection S(z) cm² | Total volume V(z) cm³ |
|------------|-----------------------|---------------|-------------|----------------------------|----------------------|
| 0 (трахея) | 1                     | 1.8           | 12.0        | 2.54                       | 30.50                |
| 1          | 2                     | 1.22          | 4.76        | 2.33                       | 11.25                |
| 2          | 4                     | 0.83          | 1.90        | 2.13                       | 3.97                 |
| 3          | 8                     | 0.56          | 0.76        | 2.00                       | 1.52                 |
| 4          | 16                    | 0.45          | 1.27        | 2.48                       | 3.46                 |
| 5          | 32                    | 0.35          | 1.07        | 3.11                       | 3.30                 |
| 6          | 64                    | 0.28          | 0.90        | 3.96                       | 3.53                 |
| 7          | 128                   | 0.23          | 0.76        | 5.10                       | 3.85                 |
| 8          | 256                   | 0.186         | 0.64        | 6.95                       | 4.45                 |
| 9          | 512                   | 0.154         | 0.54        | 9.56                       | 5.17                 |
| 10         | 1024                  | 0.130         | 0.46        | 13.4                       | 6.21                 |
| 11         | 2048                  | 0.109         | 0.39        | 19.6                       | 7.56                 |
| 12         | 4096                  | 0.095         | 0.33        | 28.8                       | 9.82                 |
| 13         | 8192                  | 0.082         | 0.27        | 44.5                       | 12.45                |
| 14         | 16384                 | 0.074         | 0.23        | 69.4                       | 16.40                |
| 15         | 32768                 | 0.066         | 0.20        | 113.0                      | 21.70                |
| 16         | 65536                 | 0.060         | 0.165       | 180.0                      | 29.70                |
| 17         | 131072                | 0.054         | 0.141       | 300.0                      | 41.80                |
| 18         | 262144                | 0.050         | 0.117       | 534.0                      | 61.10                |
| 19         | 524288                | 0.047         | 0.099       | 944.0                      | 93.20                |
| 20         | 1048576               | 0.045         | 0.083       | 1600.0                     | 139.50               |
| 21         | 2097152               | 0.043         | 0.070       | 3220.0                     | 224.30               |
| 22         | 4194304               | 0.041         | 0.059       | 5880.0                     | 350.00               |
| 23         | 8388608               | 0.041         | 0.050       | 11800.0                    | 591.00               |

Figure 3a shows the solid-state model of human TBT with regular dichotomy. First, a model was constructed for 10 generations of airways. Then one of the ends of the sixth generation was selected from each side (right and left). For these ends, starting from the seventh, two branches on each side (right and left), construction was completed in full up to the 23rd generation of the airway (Figure 3, b, c, d show enlarged fragments).

According to Weibel [2], the diameter of the lumen of the airway gradually decreases from 12.2 mm (main bronchus diameter) to 0.41 mm (diameter corresponding to the elements of the 23rd generation of the airways); the length decreases from 47.6 mm to 0.50 mm, respectively. For the 10th generation, there are 1024 pairs of airways, for the 23rd - 8388608 pairs, respectively [2]. In the constructed model, 263136 pairs of generations were obtained in aggregate.

It should be noted that this is the maximum that was possible to obtain. The model was built on a fairly powerful computer with good characteristics, which has, in particular, 16 [actually working] processors and 32 GB of RAM. An ordinary computer, which has, for example, 8 GB of RAM and 4 processors, opens the model within 24 hours. However, after the opening, it is no possible to perform any manipulation. So, for example, if you try to increase, decrease, rotate the model (or try to use any other functions of the program), computer hangs for about six hours. Therefore, to build a solid-state model of human TBT for all 23 generations of airways, an even more powerful computer is required, and the author unfortunately does not have it. Despite the difficulties, the author nevertheless succeeded in demonstrating that in the case of solving a technical problem, the simulation of human TBT for all 23...
generations of airways has already become possible. And, as computers become more powerful, the use of numerical methods for flow modeling in all 23 generations of airways also becomes possible.

Figure 3 (a, b, c, d). Solid-state model of TBT: general view (a) and enlarged fragments of the lower elements of the airways (b, c, d)

4. Conclusions
Thus, the paper shows that with significant increase in computational resources, the construction of a solid-state model of human TBT for all 23 generations of airways is possible. In the presence of a more powerful computer, the solid-state model obtained opens up the potential for using in computational experiments.

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