

CT Image-Based Segmentation, 3D Reconstruction and SLA Printing of Human Trachea

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Abstract: Several recent studies have demonstrated the feasibility and utility of trachea CT 3D reconstruction, including its ability to enhance the accuracy and safety of surgical procedures. This paper tries to emphasize on the fabrication of the 3D model of the trachea and on a pioneer study that would put in the spotlight the utility of 3D printing and reconstruction of human respiratory airways. While the fabrication process represents an important step in creating such complex geometries, it is important to understand the post-production procedures and how to apply them to obtain a geometry that will later be used in imaging and experimental simulations.

Keywords: CT image, 3D printing, trachea

I. INTRODUCTION

Trachea CT 3D reconstruction is a rapidly developing field that involves the use of advanced imaging techniques to create accurate and detailed 3D models of the trachea and surrounding structures. These models can be used for a variety of purposes, including pre-operative planning, surgical simulation, and patient education [1]–[3]. Several recent studies have demonstrated the feasibility and utility of trachea CT 3D reconstruction, including its ability to enhance the accuracy and safety of surgical procedures. In addition, these studies have highlighted the importance of using high-quality imaging data, advanced segmentation algorithms, and specialized software tools to create accurate and detailed 3D models.

Tam et al. [4] conducted a study using the 3D printing technology on trachea models. The authors stated that rapid prototyping of CT scans may be used to create a 3D model of the tracheobronchial tree, which can help with surgical or interventional planning as well as patient education and comprehension. They could also serve as a scaffold or a design assistance for a scaffold in in vitro cartilage engineering for the creation of innovative and customized implants.

Another research conducted by Bracci et al. [5] had tracheobronchomalacia as its main case point. They designed a customized tracheal splint by extracting the 3D model of the trachea of the patient from the CT scan. The authors concluded that this instance demonstrates how computer-aided design, high-resolution imaging, and three-dimensional printing of biomaterials may all work together to make it easier to create implanted devices for conditions that are anatomically particular to a certain patient.

Miyazaki et al. [6] reported a study case in which a patient that underwent single-lung transplantation procedure due to chronic obstructive pulmonary disease and later manifested stenosis at the trachea level. They created a 3D printed model prior to the procedure that allowed for preoperative planning of the surgical procedure, including decision-making related to the precise length and the hole for the upper lobe of this stent more sterically than the image of multiplanar reconstruction created by chest computed tomography. As a result, not only the surgeons but also the anesthesiologists and nurses were able to insert the airway stent safely and correctly and save the patient's life.

Though a lot of attention has been given on the preoperative planning and educational purposes, this paper tries to emphasize on the fabrication of the 3D model of the trachea and on a pioneer study that would put in the spotlight the utility of 3D printing and reconstruction of human respiratory airways with a series of future research on image analysis and experimental approach.

II. MATERIALS AND METHODS

The following steps were taken in order to subtract the tridimensional (3D) architecture of a trachea from a CT scan. The software that was used was 3DSlicer® and the post-processing of the model was later done in Blender®. To extract the trachea, an additional toolbox had to be installed. The SlicerSegmentEditorExtraEffects toolbox had been used in order to access certain functions for the segmentation process. In the beginning, the data (CT scan) used in this experiment which was acquired from a third-party was added to the workspace of 3DSlicer. After selecting the data, 4 planes were opened in the program window. 3 of which are represented by the transversal, sagittal and frontal planes of the CT and one 3D plane where segmentations are represented.

Next, the “Segment Editor” tooltip was selected from the top Modules menu. This was done in order to have access to segmentation tools for the extraction of the trachea model. Further on, the “Local Threshold” function was used. This function was important because it filled a segment in a selected region based on master volume intensity range. By doing this, it was possible to select the interior space of the trachea walls.

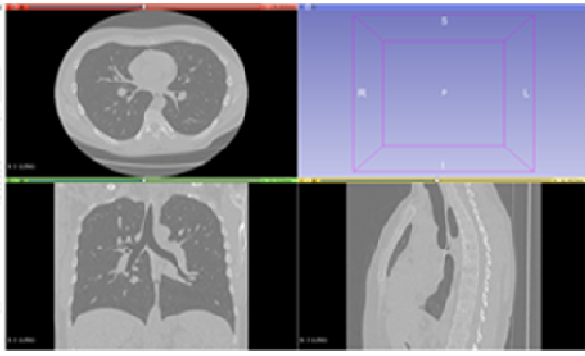


Fig. 1. Preview of the 3DSlicer interface and CT image loadout.

The next step was underlined by attributing the range for the threshold. The range was set between -1500 and -300 values. Normally, those values are representative for the presence of air. Because of this, not only the trachea model was created, but also a part of the bronchioles and lungs. This was later edited.

Another tool that was put to use was the “Paint” function which allowed to highlight the region of interest, in this case, the interior of the trachea. For this case, it is not necessary to highlight every single layer (in total, over 500 layers) for the reconstruction as they will be later automatically selected.

The next step in processing the tridimensional architecture of the trachea was to use what was selected in the previous process and to apply the “Mask Volume” function.

The final step in extracting the trachea model from the CT scan was defined by the “Fast Marching” function. As stated before, using “Paint” and this function together automatically went through all layers and automatically selected the regions which were specific with the desired threshold specified earlier. The “Fast Marching” function is a part of the SlicerSegmentEditorExtraEffects toolbox which was installed beforehand.

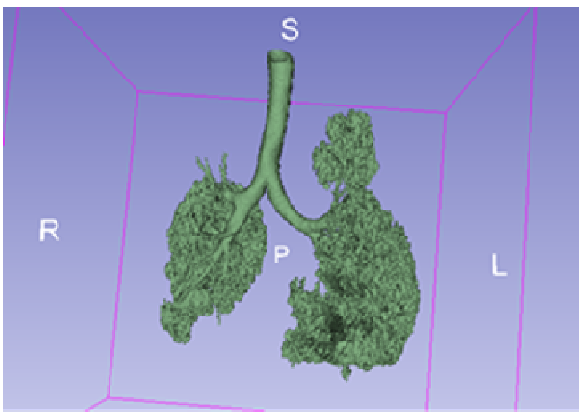


Fig. 2. Trachea and lungs segmentation completed in 3DSlicer.

The maximum volume was set to 2.00 % in order to preserve the shape at best quality. This value could have been modified, but the 2.00 % was best suited for the model at hand. Just like mentioned before, the 3D model is displayed in the 4th plane designated for this application. However, due

to the threshold values, some residual architectures of the bronchioles and lungs were also generated. Those were later removed using “Scissors” function.

The initial surface of the 3D model was not entirely sufficient for later experiments. Therefore, a smoothing function was applied. A smoothing factor of 0.10 was desired as it was best suited and did not get rid of surface details, but made them less important. The trachea was then prepared to be exported. The file needed to have the extension “.obj” in order to be later implemented into Blender for further modelling.

The OBJ file format has later been opened using Blender software for several adjustments. Several planes have been drawn to cut unnecessary geometries in the model. The segmentation has been done in a way that only the trachea and main bronchi were kept. For each part that was cut, a new plane has been created and adjusted by position in order to remove the unwanted segments.

A series of Boolean operations have been applied to extract only the trachea with the main bifurcation of bronchi. Different shapes have been created such as “Cube”, “Cylinders” and “Ellipsoid” in order to limit the bronchioles expansions. “Difference” was one of the main Boolean operations applied to cut the bronchioles from the main model. Because of the fact that the “obj” file was practically a mesh file, this process took notifiable time to complete because of the complete elimination of unwanted nodes and elements from the final model. The last removals have been made and the final result after segmentation. This was later converted and exported as a single file with the “stl” format.



Fig. 3. Segmented trachea Blender model.

After the processing executed in Blender, the final model has been achieved and this was later converted from “obj” file format to “stl” file format in order to be processed within a 3D printing software.

The “stl” file format of the trachea and main bronchi has been imported into the CHITUBOX V1.8.1 software for 3D printing. Here, several adjustments and alignments of the model have been set in order to achieve the best quality printing of the 3D printer used. First of all, a layer height of 0.05 mm has been utilized initially for the first printed model but, because of the opacity of the wall, a much smaller layer height has been set in order to redeem the transparency of the trachea. Therefore, a layer height of 0.01 mm has been used for the final model. This, indeed, made the trachea visible-through and it was the lowest value that the printer allowed for the height of a single photopolymer layer. This decision, however, slowed the printing process.

The exposure time and bottom exposure time have been set accordingly to the material that was used for printing, in this case, photopolymeric resin. In total, 10 ml of photopolymer resin have been used for 3D printing the model. The process lasted approximately 31 hours.

The 3D printer machine that was used for the printing of the geometry was ELEGOO MARS 2. This machine works with the Stereolithography 3D printing (SLA) technology.

This is part of a starting series from ELEGOO and its advantages are the easy-to-use interface as well as the vast configurability of the printing process. Depending on the layer thickness option, the objects printed could be less or more transparent (0.2 mm – opaque, 0.001 mm – transparent). However, the pieces that could be printed at a 0.01 mm layer thickness are not completely transparent, therefore several other strategies could be applied to reduce the opaque phase.

After the printing process, several steps were taken in order to assess the utility of the model and retouching methods were used to enhance the resolution of the obtained images for future experiments.

III. RESULTS AND DISCUSSION

The final result after the printing process is presented below. Before mounting the trachea in the experimental setup, a surface purification process was conducted. The model was washed in cold water for 10 minutes to get rid of the excess of resin. After that, it was let to rest in an ethylic alcohol bath for 20 minutes to make the surface smooth and to eliminate the risk of the surface interacting with other substances.



Fig. 4. Final trachea 3D printed model.

However, the resulting model was not transparent enough to do any type of experiment with it. For this, another approach was proposed which implied immersing the resulting model after the 3D printing process into its own resin. This ultimately increased the transparency of the trachea model significantly as see in Fig. 5. The immersion time for this model lasted 24 hours.

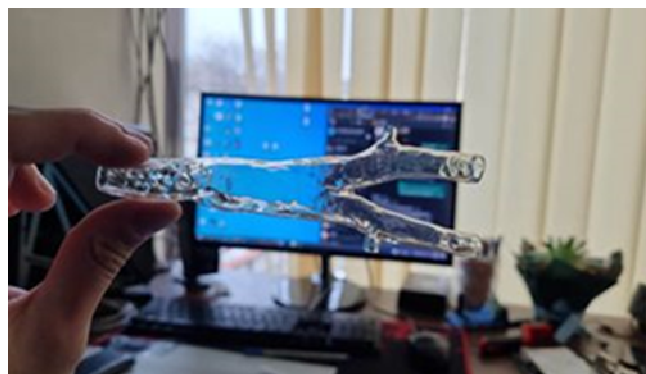


Fig. 5. Trachea model after 24h immersion in polymeric resin.

FUTURE WORK

The first imaging experiment has been conducted to replicate the presence of mucus on the interior walls of the trachea. This was the first set of images obtained for the model immersed in the same resin used for its printing. Using a high-speed camera, the movement of the simulated mucus was captured.

To simulate the mucus at the wall of the trachea, Xantan (XG) solution of 1.4% concentration has been used. The air has been induced in the geometry with a resuscitation balloon. Several behaviors of the mucus inside the trachea have been recorded and shown in Fig. 6.

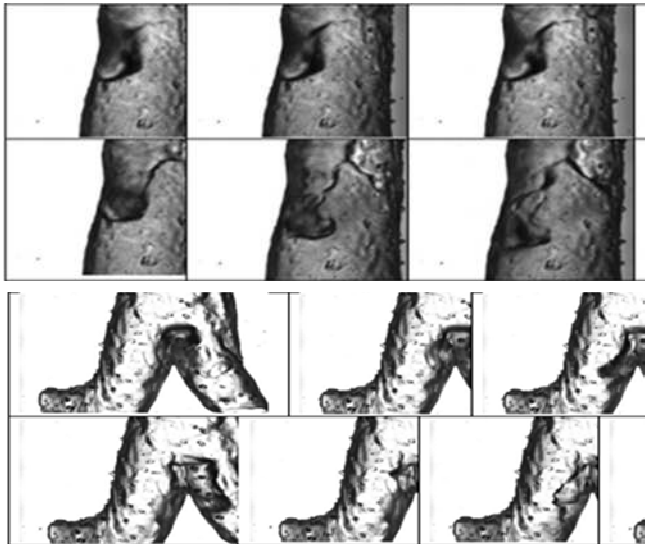


Fig. 6. Set of images obtained with a high-speed camera.

IV. CONCLUSIONS

3D printing is playing an important role in the fabrication of 1:1 scale models of different segments of the human body, more specifically for this study, the human trachea.

While the fabrication process represents an important step in creating such complex geometries, it is important to understand the post-production procedures and how to apply them to obtain a geometry that will later be used in imaging and experimental simulations of airflow and mucus movement together with it.

What is also worth mentioning is that the segmentation process could be improved by a novel AI mechanism that could automatically select the desired regions of interest for future research, but that remains a far future study.

This study, up until this point, represents an introduction to a broader research that will be conducted in order to assess different cases for control patients and patients who suffer from pulmonary complications. This first step represents a protocol for data acquisition, data processing and post-processing, data interpretation and data indexing.

Future work will include a series of studies regarding the testing for the transparency of the trachea using several other solutions for comparison. The transparency will later be assessed by spectrophotometry to have a qualitative view on the process.

Moreover, several experimental setups will be proposed to create a mechanical replica of the respiratory system. This will give us a broader look on the fluid dynamics chapter of the study and the data gathered from the experimental approach will be compared with the data processed by the CFD method.

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