



3D printed models of endobronchial valves inside bronchi airways: augmented with 3D simulation

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Abstract

Zephyr valves are one-way valves used to treat advanced emphysema by preventing air trapping and enhancing breathing. This paper presents 1) the development of 3D printed models of endobronchial (Zephyr) valves installed in the airways of the lungs and 2) the augmentation of 3D simulation for entering inside the lungs to view the Zephyr valves in the bronchi airways for training acute care nurse practitioners in the College of Nursing and the University of Alabama in Huntsville. The CT (computed tomography) scan with reconstructed slice thickness of 2.50mm was obtained from a patient with severe emphysema. The patient had one Zephyr valve inserted in the right middle lobe and three valves in the right upper lobe of the right lung. The lungs and trachea were segmented using the 3DSlicer Paint and Grow from Seeds options. The Zephyr valves were segmented using the Threshold option because of the greater density of the titanium in the valves. The valves were printed using a resin printer which provided more detail. 3D animation was added by using the 3DSlicer Save option. An auto-run file loads all the necessary files for the animation. The Segmentation 3D Opacity was set at 20% to view the bronchi and Zephyr valves inside the lungs. The 3D printed models and animation are being integrated into the acute care training for nurse practitioners to supplement their education.

Keywords: Zephyr valves, emphysema, 3D printing, 3D animation, lungs

1. Introduction

The Zephyr Endobronchial Valve System is the first FDA approved, minimally invasive device available in the U.S. for treating patients with severe emphysema who consistently feel short of breath despite using COPD (Chronic Obstructive Pulmonary Disease) medications and/or oxygen. In severe cases of emphysema, air becomes trapped in the lungs and hyperinflation occurs, thus preventing new air from entering the lungs and causing shortness of breath.

A Zephyr valve is a one-way valve that allows trapped air to escape when breathing out, but prevents new air from entering the damaged part of the lungs. The Zephyr valve allows healthy portions of the lungs to expand, lifting pressure off the diaphragm to enhance breathing (Lovering, 2022).

A medical doctor uses a bronchoscope with a camera to place the Zephyr valves in the airways of the lungs. Multiple valves are generally inserted. Figure 1 is a sketch of the Zephyr valve (Pulmonx, 2023). The diameter of the valve ranges from 5.2–8.0mm and the



length from 4.0–8.0mm.

A related study by Ho et al., (2019) developed several multi-level 3D printed models for simulating a bronchoscopy. Of interest was the use of a 3D printer with a multi-material jet capable of fusing plastic and rubber for printing a flexible airway. The 3D printed tracheobronchial anatomy with third order bronchi was achieved from a CT (computed tomography) scan with a 256 slice series (1.00mm slices).

The use of simulation for training and assessment for central venous catheter skills is well documented and advocated by the American Thoracic Society Skills-based Working Group (McSparron et al., 2015).

Han et al., (2015) developed a 3D printed model for airway evaluation. The model was used in a pre-anesthesia plan.

The objective of this study was two-fold: 1) to develop 3D printed models of the Zephyr valves located in the airways of the lungs and 2) to augment the models with 3D animation for visually entering the lungs and observing the Zephyr valves. The 3D printed models and animation are being integrated into the acute care training for nurse practitioners in the College of Nursing (CoN) at the University of Alabama in Huntsville (UAH).

The focus of this paper is on:

- Software used to meet the above objective.
- Steps in developing the 3D printed models and 3D animation.
- 3DSlicer segmentation methods.
- Anticipated use in training acute care nurse practitioners.



Figure 1. Zephyr valve (Pulmonx, 2023).

2. Methodology

A CT scan was obtained from a middle-aged female with severe emphysema. The patient had undergone the placement of three one-way Zephyr valves to accomplish total occlusion of the right upper lobe (RUL) of the right lung. Several days later a fourth valve was installed in the right middle lobe (RML) (Figure 2). The CT scan was performed without contrast and was reconstructed with a slice thickness of 2.50mm.

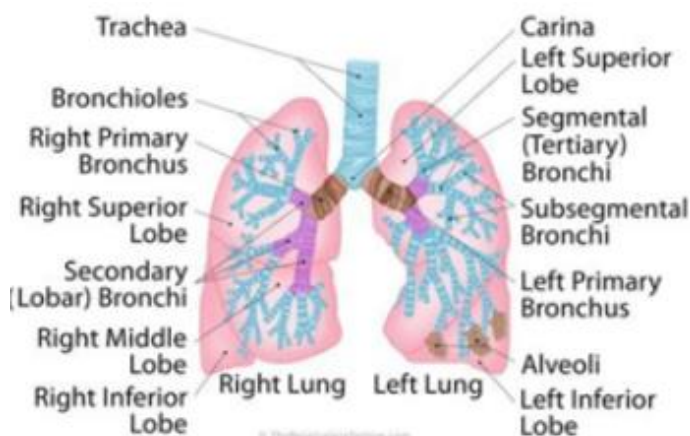


Figure 2. Bronchi anatomy (The Respiratory System, 2017).

3DSlicer is a free, open source software application for the three-dimensional visualization and analysis of medical images. 3DSlicer segmentation of images is a procedure to delineate regions in the image. It is a very common procedure in medical image computing and required for masking, visualization of structures, measuring volume and 3D printing. Segmentation may be performed manually by iterating through slices of an image; however, more often semi-automatic or automatic methods are used (3DSlicer, 2022).

The 3DSlicer Segment Editor module used two options to segment the structures: 1) Threshold and 2) Paint and Grow from Seeds. The Smoothing algorithms will smooth a segment by filling in holes and removing extrusions. No smoothing was used on any of the segments in this study to maintain model detail.

The 3DSlicer Threshold range of -1024 to 3071 is similar to the Hounsfield Unit (HU) which makes up the gray scale in medical CT images. The HU unit is used by radiologists in the interpretation of CT images. It is a quantitative scale from -1024 (black) representing air to 3071 (white) representing the densest tissue in the human body. Dense bones absorb much of the radiation while soft tissue (muscle, fat and organs), allowing more of the x-rays to pass through them. As a result, bones appear white on the x-ray (HU +1000), soft tissue shows up shades of grey (HU -100 to +80) and air shows up black (HU lungs -500), and air -1000). The Zephyr valve has a titanium

mesh and consequently appeared white and had a high threshold value.

The 3DSlicer Paint option will color a selected anatomical structure. Grow from Seeds option is then used with the Paint option (where a few seeds were placed) and then grows them to achieve a complete segmentation. Painting a few seeds in each plane (axial or transverse, coronal and sagittal) resulted in a segmented lung with no leaks. A small amount of leaks occurred in the segmented trachea; however, these leaks were easily repaired with the Scissors option.

The Paint and Grow from Seeds options were also used to segment the Zephyr valves. However, considerable segment cleanup was necessary. As a result, the valve detail was minimal as shown in Figures 3 and 4. On the other hand Threshold provided a greater detail in the segmented model (Figure 5). The Threshold valve was set at 180 Hounsfield Units.

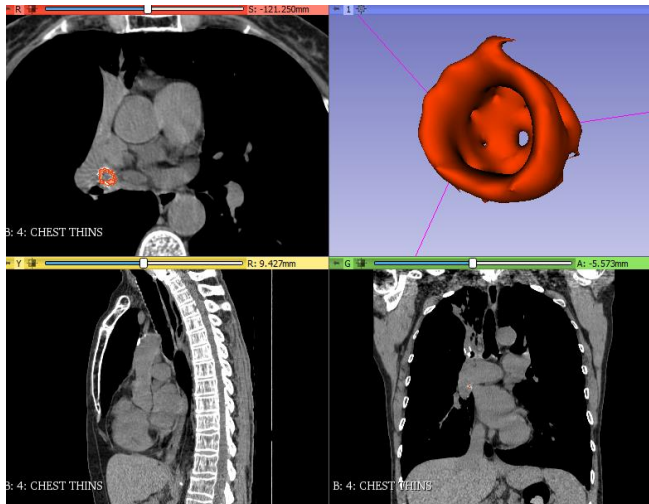


Figure 3. 3DSlicer model for the valve at the right middle lobe of right lung.

Figures 6–8 show the valves in the CT scan in several of the axial planes. The Zephyr valves in Table 1 are located between the CT slices.

Table 1. Location of Zephyr valves.

Zephyr valve	CT Slice range
Valve1 (right middle lobe)	-128.0 to -116.0mm
Valve2 (right upper lobe)	-88.0 to -78.0mm
Valve3 (right upper lobe)	-81.0 to -68.5mm
Valve4 (right upper lobe)	-78.0 to -68.5mm

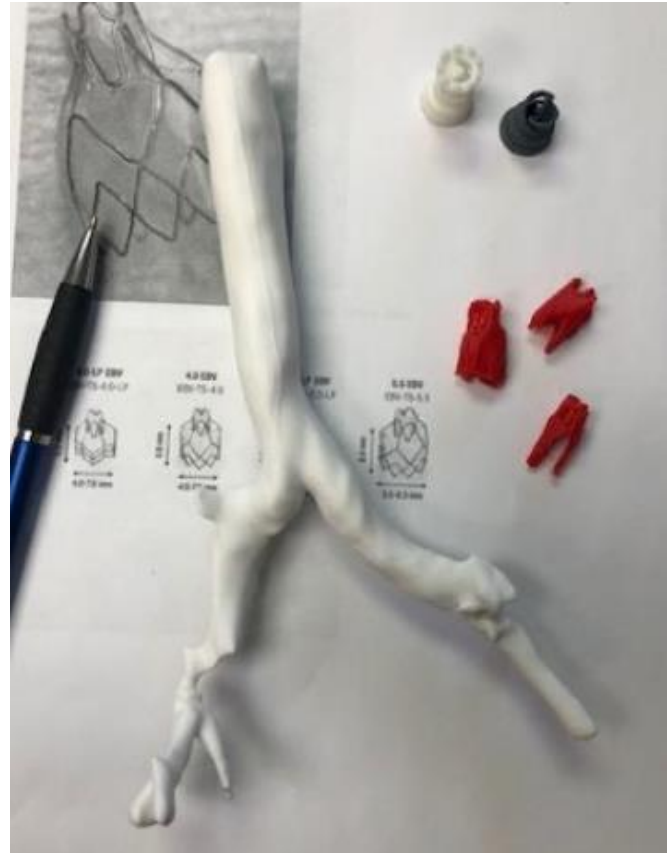


Figure 4. Zephyr valves printed using Paint and Grow from Seeds.

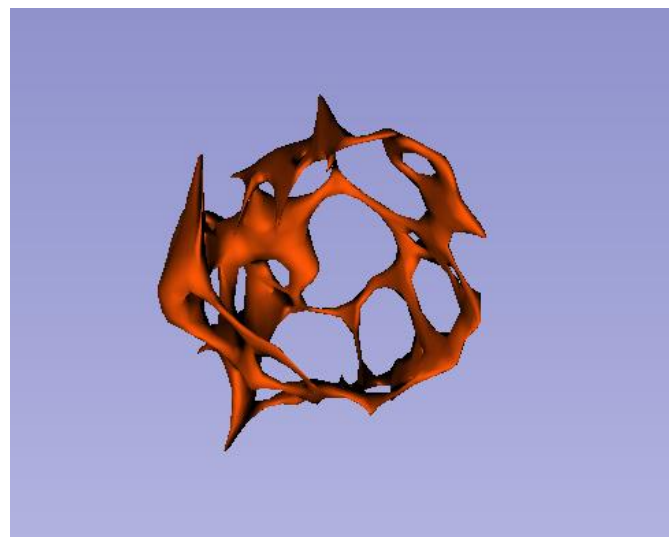


Figure 5. 3DSlicer model of Zephyr valve at right middle lobe of lung using Threshold.

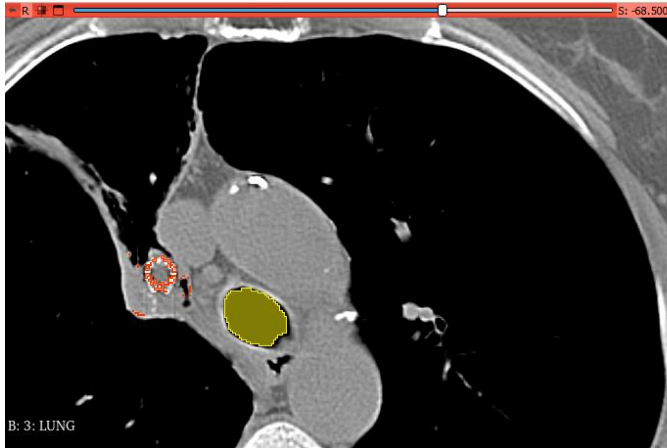


Figure 6. CT scan in axial plane, slice S= -68.5mm, at right upper lobe.

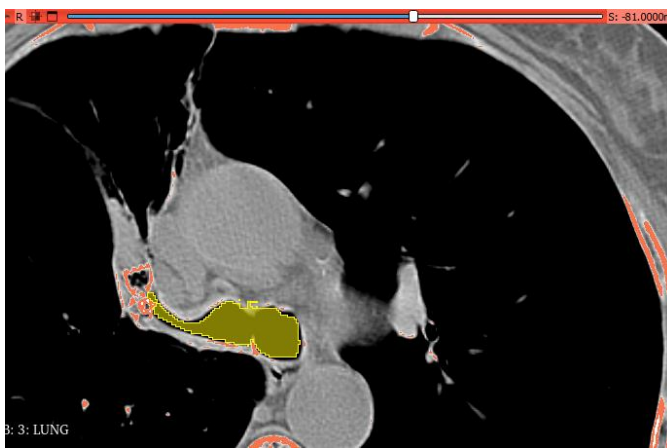


Figure 7. CT scan in axial plane, slice S= -81.0mm, at right upper lobe.



Figure 8. CT scan in axial plane, slice S= -123.0mm, at right middle lobe.

3DBuilder is a free 3D modeling software from Microsoft for designing 3D models, visualizing models and quickly modifying models. The software is installed by default on all computers running Windows 10 or newer. More importantly, 3DBuilder is used to visualize medical images in STL (stereolithography) and helpful in identifying extraneous objects that need

to be removed before 3D printing.

The 3D printing of a model from the CT scan consisted of the following steps:

- Step1: Obtain CT scan with reconstructed images in DICOM (Digital Imaging and Communications in Medicine) format.
- Step2: Use 3DSlicer to anonymize the data set into NRRD (Nearly Raw Raster Data) format.
- Step3: Use 3DSlicer to segment desired structures (lungs, trachea and Zephyr valves) from the CT scan.
- Step4: Download the segmented models in STL (stereolithography) format.
- Step5: Use 3DBuilder to review the segmented models.
- Step6: Use PrusaSlicer to clean up the lungs and trachea models, fit the models into the print volume and add support structures.
- Step7: Use Autodesk Fusion360 software to clean up the Zephyr valve models, fits the models into the print volume and add support structures.
- Step8: Use PrusaSlicer or Chitbox to convert the appropriate STL files into the G-code for the 3D printer.
- Step9: Download G-code onto 3D printer.
- Step10: Print the models.
- Step11: Post-processing of resin models of the Zephyr valves, especially post-curing.

The lungs and trachea were printed on a Prusa i3MK3S+ 3D printer using a 1.75mm diameter PLA (polylactic acid) filament. The print volume was 25x21x21cm; therefore, the lungs were printed as a left lung and right lung.

The Zephyr valves were printed on an Elegoo Saturn2 resin printer using a photopolymer resin (8K resin for the gray models and 4K resin for the translucent models). The print volume was 19.2x12x20cm.

The steps to create the 3D animation after Step4 above are:

- Step5: Use the 3DSlicer Save option to save the necessary files. 3DSlicer will display the required files (an auto-run file and the NRRD files of the segmented models). Generally these files are saved in a separate folder along with the STL files.
- Step6: Click on the auto-run file. All the necessary files will be loaded along with 3DSlicer. The standard 3DSlicer display will appear (Figure 3).
- Step7: Click on the square icon in the tool bar and select 3DOnly to obtain a full screen of the 3D models. The model can be enlarge and rotated with the cursor. To return click on the Four-Up option in the tool bar.

- Step8: If desired, return to the Segment Editor module and turn off the segment “eyes” to remove or add segments.
- Step9: To look inside the lungs, use the Segmentation module, select the Advanced option and use the Opacity bar to vary the opacity of the lungs. A value of 20% was used in this study.

3. Results and Discussion

Figure 9 shows the Zephyr valves inside the lungs. Figure 10 shows the lungs with a 20% opacity setting in 3DSlicer.

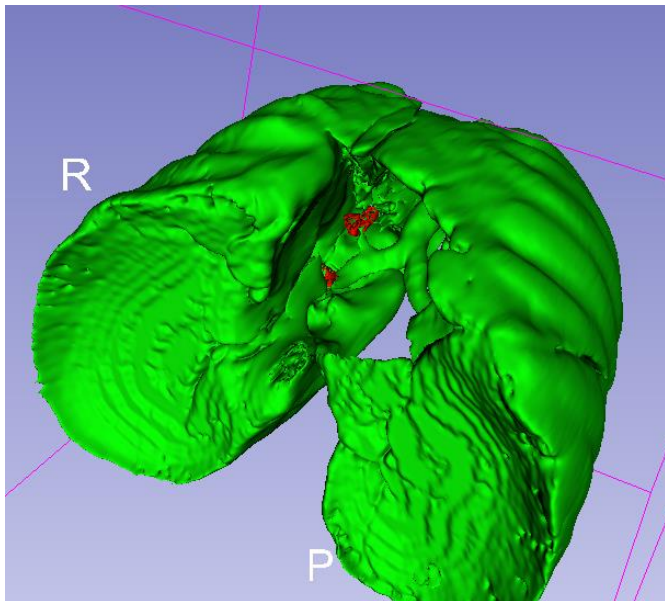


Figure 9. 3DSlicer model of lungs with Zephyr valves.

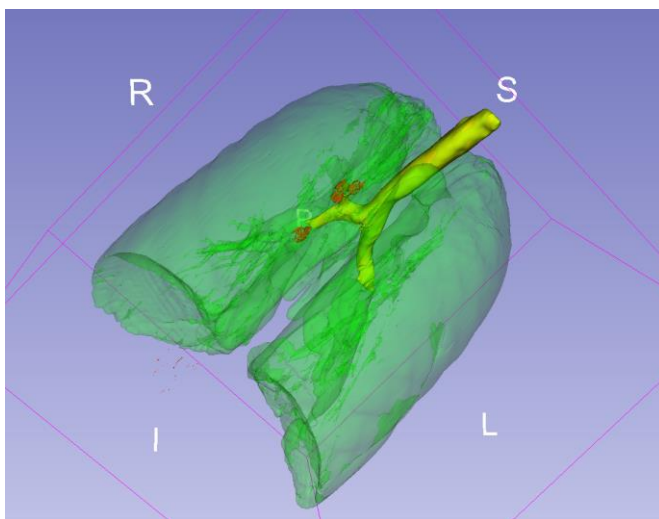


Figure 10. 3DSlicer model with opacity=20%.

Figure 11 shows the trachea and valves with the lungs removed. The Zephyr valves are shown in red.

The right lung is divided into three lobes: 1) right upper lobe with three segments, 2) right middle lobe

with two segments and 3) right lower lobe with five segments). Three Zephyr valves were installed in the right upper lobe and one valve in the right middle lobe.

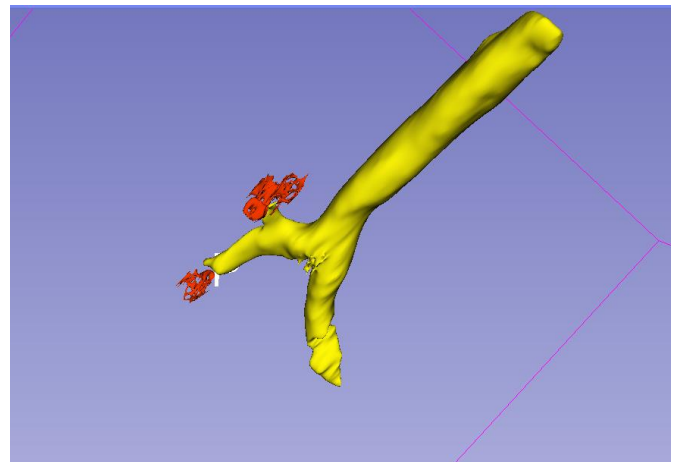


Figure 11. 3DSlicer model of trachea and valves.

Figure 12 shows a close-up of the four Zephyr valves which were segmented using a 3DSlicer Threshold=180. As a result, there is more detail than the valves segmented using Paint and Grow from Seeds. Figure 13 shows the Zephyr valves in the airways with the left valve being the lower valve on the right middle lobe.

Figure 14 shows the 3D printed resin valves. Figure 15 is a close-up of the three valves installed in the right that were installed in the right upper lobe. Figure 16 shows the resin valve that was installed in the right middle lobe (in two colors of resin) with an original Zephyr valve.

The dimensions of the lower valve on the right middle lobe were 9-11mm in diameter (valve slightly oval) and 11-15mm in length. The actual diameter of the Zephyr valve ranges from 5.2-8.0mm and the length from 4.0-8.0mm (numbers are from the manufacturer).

Limitations of this study were the challenges of obtaining the correct dimensions of the valves primarily due to difficulties in 3DSlicer segmentation. There are several reasons for this discrepancy. One obvious reason is the long “spikes” extending from the 3D printed valves and resulting from the segmentation of the valves using 3DSlicer. These spikes are generally removed by the Smoothing option in Slicer. However, the Smoothing option will remove model detail. With the Zephyr valve it was of interest in seeing this detail as shown in Figure 14 with the resin printed valves.

Another reason for this discrepancy is because of the quality of metallic structures such as the titanium frame of the Zephyr valve. These structures will result in “starbursts,” or extrusions, which lead to

difficulties in 3DSlicer segmentation. As an example, dental fillings on a CT scan will cause “starbursts” because the x-rays cannot pass through the amalgam fillings. Figure 17 shows these extrusions in 3DSlicer. Metal artifact reduction algorithms can be used to improve the CT images. Also, various options exist in 3DSlicer to cleanup these extrusions; however, generally at the expense of model detail.

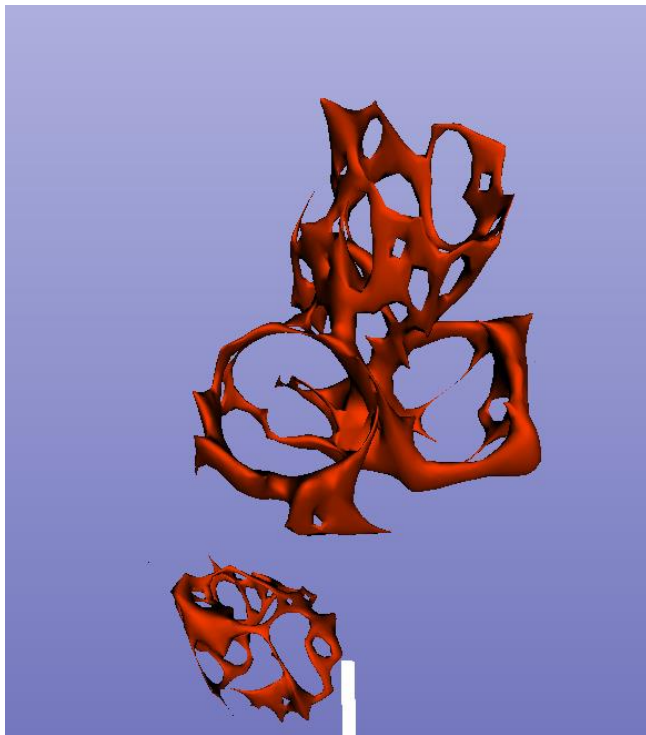


Figure 12. 3DSlicer model of Zephyr valves with Threshold=180.

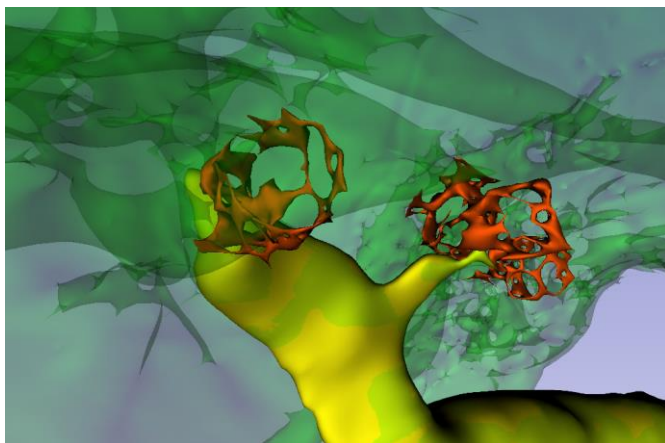


Figure 13. Close-up 3DSlicer model of Zephyr valves inside lungs.

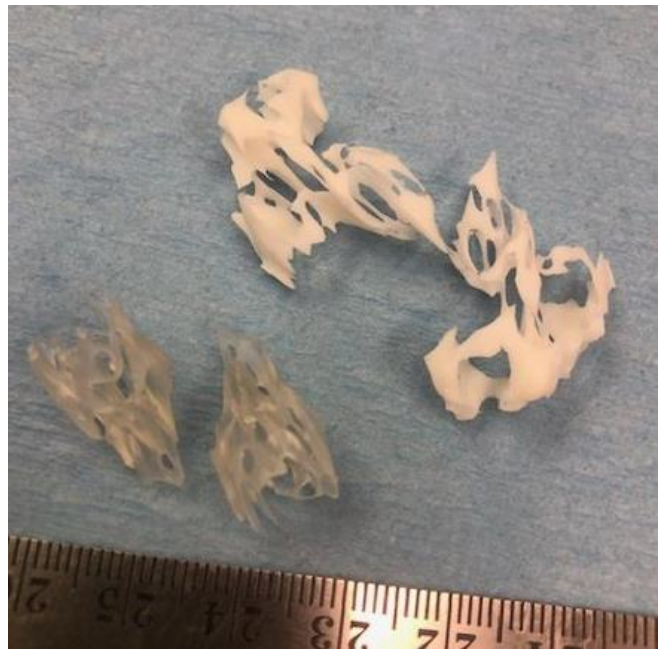


Figure 14. 3D printed resin Zephyr valves.



Figure 15. Close-up of the three 3D printed resin Zephyr valves.



Figure 16. Comparison of resin valve with actual Zephyr valve.

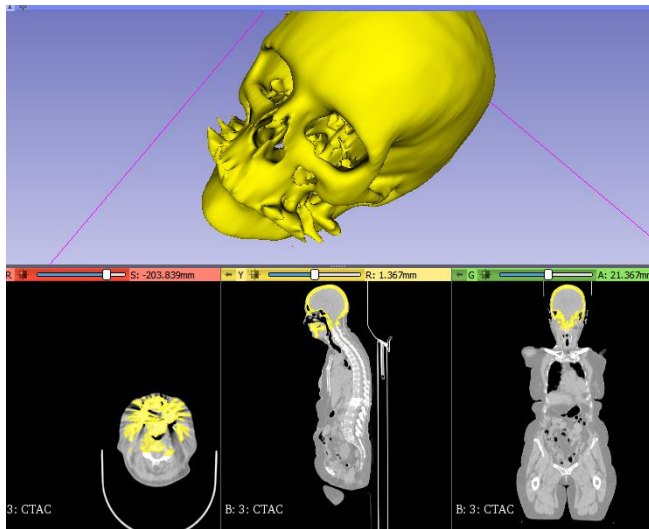


Figure 17. “Starbursts” resulting from teeth fillings.

4. Conclusions

This paper describes the development of 3D printed models of Zephyr endobronchial valves placed in emphysematous lungs to augment the models with 3D animation for visually entering the lungs, the valves’ 3DSlicer segmentation methods, and the anticipated use in training acute care nurse practitioner students.

In summary the following conclusions are made:

- The lung was easily segmented with no leakage using the 3DSlicer Paint and Grow from Seeds. The key to the segmentation was the painting of seeds in the axial, coronal and sagittal planes. Painting in three slices of only the axial plane resulted in leakage which had to be cleaned up using Scissors.
- The trachea was also segmented with minimal leakage by painting in three slices in only the axial plane.
- The Zephyr valves were segmented using Threshold because of the dense material titanium. The Threshold was set at 180 Hounsfield Units. The valves were also segmented using the Paint and Grow from Seeds; however with less resolution.
- The resin printed Zephyr valves had considerable detail, however they were fragile even after curing and difficult to handle.
- The 3D animation was added by using the 3DSlicer Save option. This feature was also used to reload and make changes to a previous model. Once the files were reloaded the Segmentation 3D Opacity was set at 20% to view the bronchi and Zephyr valves inside the lungs.
- The 3D printed model of the trachea did not extend beyond the locations of the Zephyr valves. This may have resulted from the voids that were created because of the titanium. The

Paint and Grow from Seeds stopped at the valves.

- The 3D printed models of the lungs, trachea and Zephyr valves were excellent additions in the training of acute care training for nurses.

To date the feedback from the faculty has been very positive. Several areas of further investigation have been identified. One area is the effect of slice thickness on 3D printing the trachea. The trachea printed by Ho et al., (2019) was from a CT with a 1.00mm slice thickness. On the other hand, the CT in this study had a slice thickness of 2.50mm.

A second area of further investigation is the bronchi not extending beyond the Zephyr valves. It may be that 3DSlicer stops segmenting once reaching a valve which has a different density that the trachea.

The 3D printed models and animation are being integrated into the acute care training for nurse practitioners. In the fall 2023 the files for the 3D animation will also be provided to students for their individual study. A recent paper by Lakin et al., (2023) describes the development of the stand along 3D computer simulation/animation of the four Zephyr valves attached to the bronchial airways inside the lungs and enclosed in the chest. Students are given copies of the simulation to run on their computers where they can zoom, rotate and fly into the lungs to observe the Zephyr valves.

Acknowledgements

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