# Development of a customized three-dimensional airway model

## Desenvolvimento de um modelo tridimensional customizado de vias aéreas

## Desarrollo de un modelo de vía aérea tridimensional personalizado

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**Abstract**
This study aimed to develop a customized, three-dimensional airway model based on relevant medical images, using additive manufacturing techniques. We evaluated the model's ability to replicate the dimensions of the images acquired from the chest of a patient using multi-detector computed tomography (CT). Using dedicated software, a three-dimensional mesh was created based on the images. A multi-detector CT study of the full-scale printed three-dimensional airways model was subsequently carried out to compare its dimensions with that of the original study at four predetermined points. The observed median differences at the four points were 0.4 mm ($p$ = 0.686), -1.3 mm ($p$ = 0.138), 0.7 mm ($p$ = 0.141), and 0.1 mm ($p$ = 0.892). The intraclass correlation coefficient between the measurements made on the patient and those on the model was 0.98 (95% confidence interval: 0.96–0.99, $p$ < 0.001). We successfully developed a three-dimensional model of the airway based on its corresponding medical images. The differences in the dimensions between the model and the original images were in line with those observed in previous studies and are presumably irrelevant for most applications.
**Keywords**: Printing, Three-Dimensional; Multi-detector Computed Tomography; Simulation; Training.

**Resumo**
Este estudo teve como objetivo desenvolver um modelo de vias aéreas tridimensional customizado com base em imagens médicas relevantes, usando técnicas de manufatura aditiva. Avaliamos a capacidade do modelo de replicar as dimensões das imagens adquiridas do tórax de um paciente usando tomografia computadorizada (TC) de múltiplos detectores. Usando um software dedicado, uma malha tridimensional foi criada com base nas imagens. Um estudo de TC com múltiplos detectores do modelo tridimensional de vias aéreas impresso em escala real foi posteriormente adquirido para comparar suas dimensões com as do estudo original em quatro pontos pré-determinados. As diferenças medianas observadas nos quatro pontos foram 0,4 mm (p = 0,686), -1,3 mm (p = 0,138), 0,7 mm (p = 0,141) e 0,1 mm

(p = 0,892). O coeficiente de correlação intraclasse entre as medidas do paciente e do modelo foi de 0,98 (intervalo de confiança de 95%: 0,96–0,99, p < 0,001). Desenvolvemos com sucesso um modelo tridimensional da via aérea com base em suas imagens médicas correspondentes. As diferenças nas dimensões entre o modelo e as imagens originais estavam de acordo com as observadas em estudos anteriores e são presumivelmente irrelevantes para a maioria das aplicações.
**Palavras-chave**: Impressão 3D; Tomografia Computadorizada Multidetectores; Simulação; Treinamento.

**Resumen**

Este estudio tuvo como objetivo desarrollar un modelo de vía aérea tridimensional personalizado basado en imágenes médicas relevantes, utilizando técnicas de fabricación aditiva. Evaluamos la capacidad del modelo para replicar las dimensiones de las imágenes adquiridas del tórax de un paciente mediante tomografía computarizada (TC) multidetector. Usando un software dedicado, se creó una malla tridimensional basada en las imágenes. Se adquirió un estudio de TC multidetector del modelo tridimensional a gran escala de la vía aérea para comparar sus dimensiones con las del estudio original en cuatro puntos predeterminados. Las medianas de las diferencias observadas en los cuatro puntos fueron de 0,4 mm (p = 0,686), -1,3 mm (p = 0,138), 0,7 mm (p = 0,141) y 0,1 mm (p = 0,892). El coeficiente de correlación intraclase entre las medidas del paciente y del modelo fue de 0,98 (intervalo de confianza del 95 %: 0,96-0,99, p < 0,001). Hemos desarrollado con éxito un modelo tridimensional de la vía aérea a partir de sus correspondientes imágenes médicas. Las diferencias en las dimensiones entre el modelo y las imágenes originales estaban en línea con las observadas en estudios previos y presumiblemente son irrelevantes para la mayoría de las aplicaciones.
**Palabras clave**: Impresión tridimensional; Tomografía Computarizada Multidetector; Simulación; Capacitación.

## 1. Introduction

Additive manufacturing techniques, commonly called “3D printing,” are widely used in the industry and have recently been recognized as tools of potential value for medical teaching, preoperative planning, and development of orthotics and prostheses. (Hoang et al., 2016; Langridge et al., 2018; Matsumoto et al., 2015; Mitsouras et al., 2015)

Among medical specialties, radiology and imaging diagnosis play a central role in this new technology as models developed using additive manufacturing techniques are, with a few exceptions, based on three-dimensional reconstructions of sectional images acquired primarily using multi-detector computed tomography (MDCT) and magnetic resonance imaging. (Matsumoto et al., 2015; Mitsouras et al., 2015)

The most common clinical applications of additive manufacturing are in buccomaxillofacial surgery, neurosurgery, pulmonology and thoracic surgery, cardiovascular surgery, orthopedics, radiotherapy, and abdominal surgery. (Hoang et al., 2016; Langridge et al., 2018; Matsumoto et al., 2015; Mitsouras et al., 2015) The pneumological applications include the ability to print the airways, thoracic cavity and dorsal column, lungs, and the mediastinum.(Giannopoulos et al., 2016) These applications highlight promising areas where they could be useful, including training for endoscopic airway evaluation, and preoperative(Akiba et al., 2014) and airway prosthesis (Miyazaki et al., 2015) assessment.

The value of simulated training in bronchoscopy has been well established,(Colt, 2013) and its use is recommended by several specialty societies.(Ernst et al., 2015) However, the high costs of mannequins and equipment limit its widespread use in training programs. To overcome these limitations, various centers have developed low-cost three-dimensional models that simulate the airways for endoscopic training.(AL-Ramahi et al., 2016; Bustamante et al., 2014; Byrne et al., 2016; Parotto et al., 2017; Pedersen et al., 2017) However, potential limitations in the reliability of these models have been demonstrated; therefore, model validation and accuracy control are fundamental requirements, particularly for models used for teaching, training, and therapeutic planning. (George et al., 2017)

In this study, we aimed to develop a customized, three-dimensional airway model based on medical images, and assess the reliability of its dimensions in relation to the original images obtained by MDCT.

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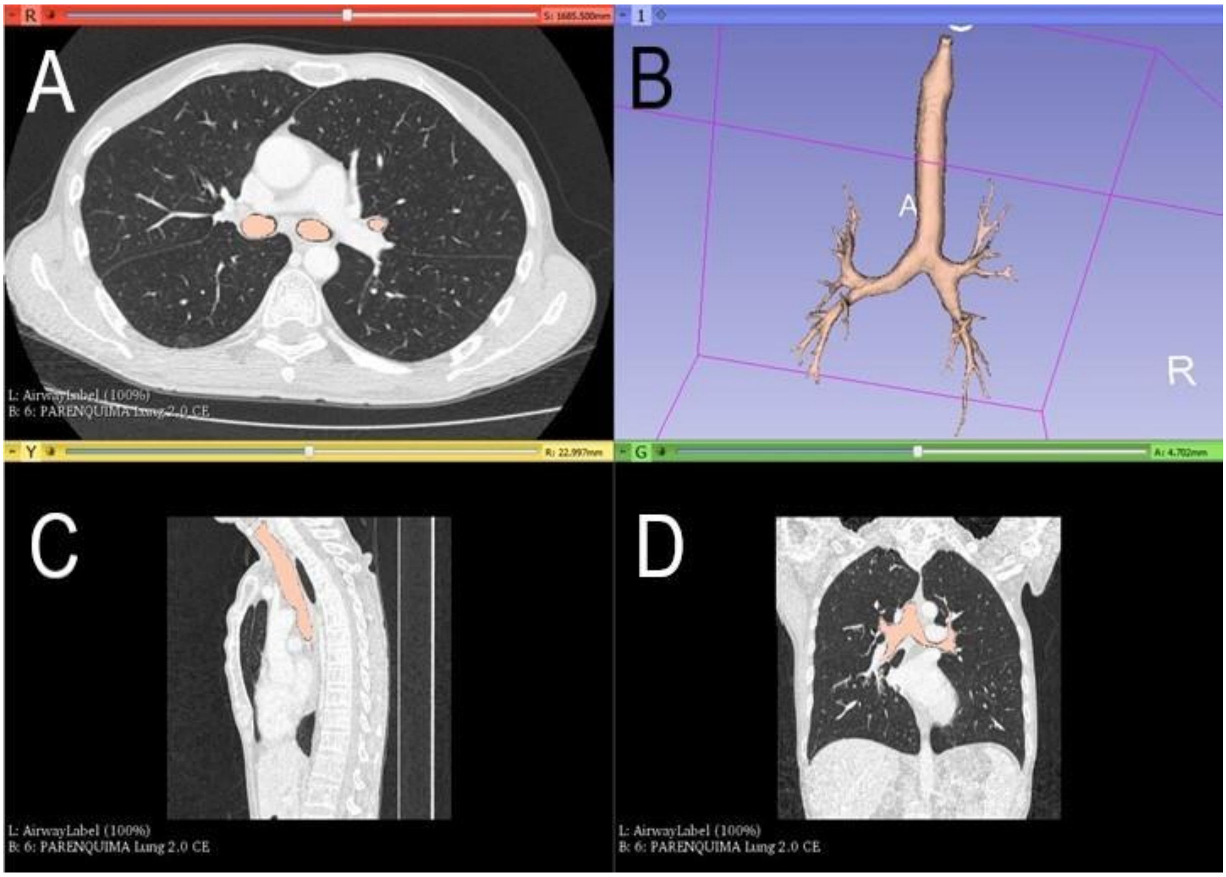
## 2. Methodology

The Research Ethics Committee of the Hospital de Clínicas de Porto Alegre of the Federal University of Rio Grande do Sul approved this study (No. 2,560,404, dated March 23, 2018). Due to its retrospective and anonymised nature the board waived the need for written informed consent.

### 2.1 Three-dimensional model printing

We selected airway images which had previously been acquired by chest MDCT (SOMATOM Emotion, Siemens Healthcare, Erlanger, Germany) of a 48-year-old male patient. The scan was performed with 16 rows of detectors and a tube voltage of 120 kVp with automatic exposure control. The images, obtained from the institution's image storage system, were anonymized. Subsequently, segmentation of the aerial column (the trachea and main bronchi) and creation of the three-dimensional mesh were performed with the 3D Slicer software (http://www.slicer.org/; Figure 1). The three-dimensional mesh was post-processed using the Meshmixer (Autodesk, Inc., San Rafael, CA, USA). The printing process was performed on a B9 Core Series printer (B9 Creations, Rapid City, SD, USA) using photosensitive resin deposition. Through the process, we sought greater malleability, strength, precision, and more reliable detailing to adequately represent the anatomy of the trachea and the main, lobar, and segmental bronchi. The average time to generate the model was approximately 4 days. The impression was the longest stage and took 2–3 days. The software used in the study is freely available in the public domain.

**Figure 1.** A: MDCT of the thorax, axial section. B: Three-dimensional mesh of the airways. C: MDCT of the thorax, sagittal section. D: MDCT of the thorax, coronal section. *MDCT, multi-detector computed tomography.*



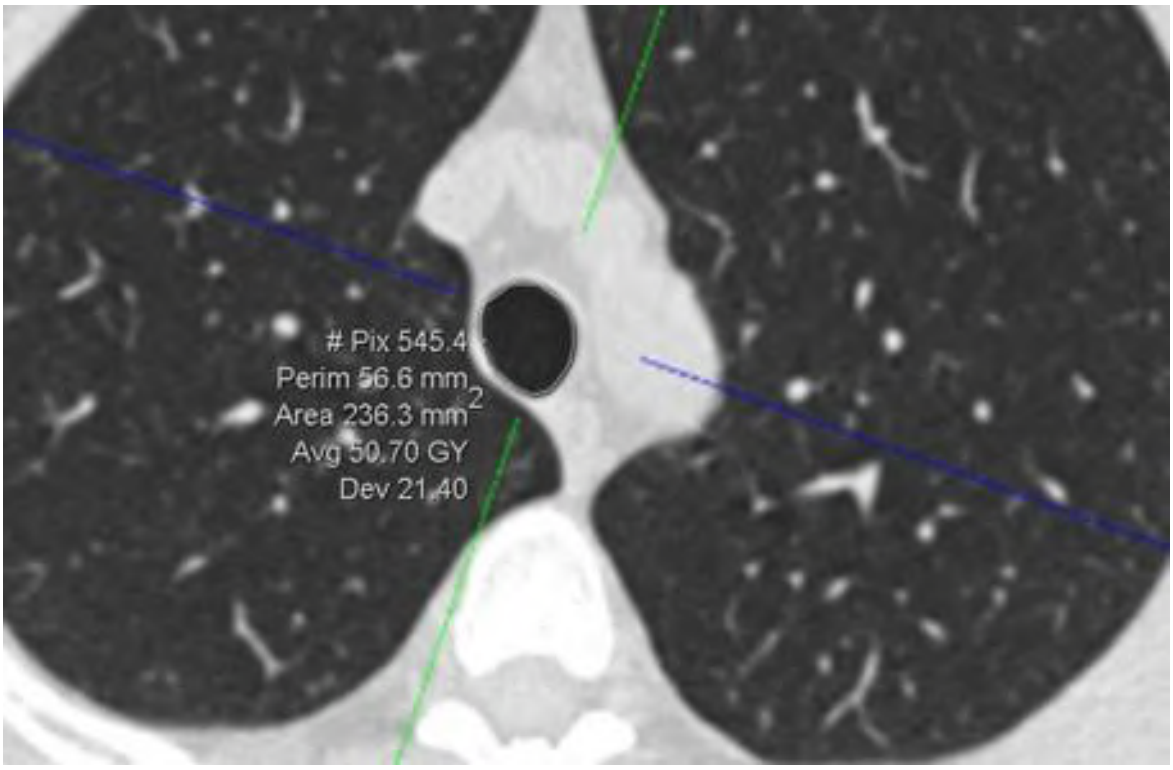

Source: Authors.

**2.2 Evaluation of thorax MDCT and the three-dimensional model**

A 64-row MDCT study of the printed three-dimensional model was performed on an Aquilion CXL scanner (Canon Medical Systems, Ota City, Tokyo, Japan). The images were acquired using a tube voltage of 80 kVp and a tube current of 30 mA. The data were reconstructed with the same slice thickness and range as the original computed tomographic images (1.0 and 0.5 mm, respectively). Both studies (chest and printed three-dimensional model MDCT) were analyzed with a dedicated workstation software (IMPAX v. 6.6.1.3525, Agfa HealthCare NV, Mortsel, Belgium), using multiplanar and three-dimensional reconstructions.

The lead researcher extracted four images from the data of both MDCT studies using multiplanar reconstructions. The images were at four predetermined locations: 1.5 and 3.0 cm proximal to the tracheal carina, and 2 cm distal to the origin of the right and left main bronchi. Five trained observers (all thoracic radiologists at our institution) performed the four-airway internal perimeter measurements (Figure 2). The measurements were from the interface between the tracheal wall and tracheal lumen, not including the wall. The observers first measured the three-dimensional model, and 10 days later, the original tomographic examination. The observers were blinded to the measurements made by the other observers.

**Figure 2.** Internal perimeter measurement.




Source: Authors.

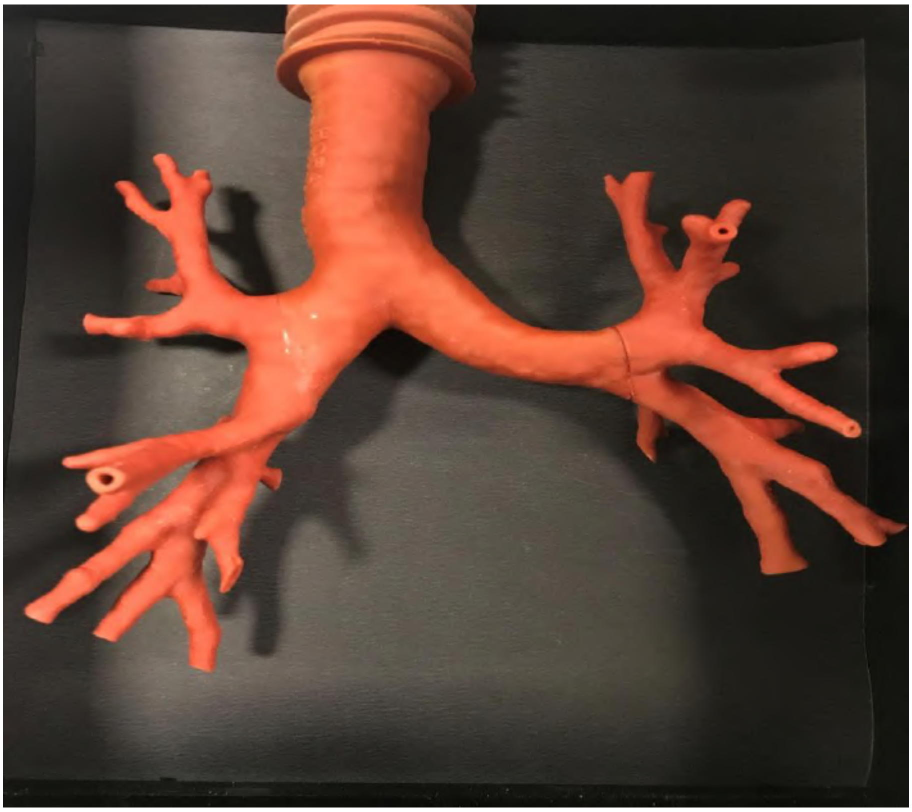
**2.3 Statistical analysis**

Data analysis was performed using IBM SPSS for Windows, Version 20.0 (IBM Corp., Armonk, NY, USA). The variables, described as the median, minimum, and maximum, were compared using the Wilcoxon rank-sum test. We also calculated the intraclass correlation coefficient between the measurements to evaluate the interobserver variability. Differences with a *p*-value < 0.05 were considered statistically significant.

## 3. Results

A three-dimensional full-size airway model was developed (Figure 3). The direct cost of developing the model was US$ 91.08, in which 80 mL of photosensitive resin cost US$ 40.70 and the acrylic box for the finished model cost US$ 50.39. Indirect costs, such as employee time and printer purchase, were not measured, as they were available at the institution. The model and patient perimeter measurements were similar for all measured sites (Table 1).

**Figure 3.** A printed 3D airway model.



Source: Authors.

**Table 1**. Descriptive and comparative table of the patients and model measurements[a]

| | Patient | Model | Difference | *p*-value |
|---|---|---|---|---|
| Trachea 1.5[b] | 60.1 (56.7–61.5) | 58.7 (57.5–60.0) | 0.4 (-1.9–2.3) | 0.686 |
| Trachea 3.0[c] | 57.6 (55.4–59.2) | 58.2 (58.1–59.5) | -1.3 (-2.7–0.4) | 0.138 |
| Right bronchus | 46.7 (44.9–47.5) | 45.8 (45.3–46.1) | 0.7 (-0.4–1.4) | 0.141 |
| Left bronchus | 45.5 (44.1–47.3) | 45.4 (44.4–46.0) | 0.1 (-0.3–1.3) | 0.892 |

[a]Data are presented in millimeters as median (minimum–maximum) and compared using the Wilcoxon rank-sum test. [b]Measurement performed in the trachea, 1.5 cm proximal to the carina. [c]Measurement performed in the trachea, 3.0 cm proximal to the carina. Source: Authors.

The intraclass correlation coefficient calculated between medians of the measurements of the patient and the model at the four points was 0.98 (95% confidence interval: 0.96–0.99, $p < 0.001$) (Table 2).

**Table 2**. Intraclass correlation coefficient between the patient and model measurements.

| | ICC (95% CI) |
|---|---|
| Trachea 1.5[1] | 0.54 (-0.47–0.94) |
| Trachea 3.0[2] | 0.47 (-0.55–0.93) |
| Right bronchus | 0.45 (-0.57–0.92) |
| Left bronchus | 0.76 (-0.14–0.97) |
| All[3] | 0.98 (0.96–0.99) |

[1]Measurement performed in the trachea, 1.5 cm proximal to the carina.
[2]Measurement performed in the trachea, 3.0 cm proximal to the carina.
[3]The four points considered together.
ICC, interclass correlation coefficient; CI, confidence interval.
Source: Authors.

## 4. Discussion

In this study, we developed a three-dimensional airway model based on computed tomographic images, using additive manufacturing techniques. Additionally, we demonstrated that the maximum median airway perimeter difference between the model and the original image was 1.3 mm. This difference, which corresponded to a difference of 0.41 mm of the airway caliber, was statistically insignificant. Our results correspond with those of previous studies,(Barker et al., 1994; Choi et al., 2002; Frühwald et al., 2008; George et al., 2017; Ibrahim et al., 2009; Petropolis et al., 2015; Salmi et al., 2013; Taft et al., 2011; Wu et al., 2015) which have reported a sub-millimeter diameter difference between the three-dimensional model and the original MDCT images.

Previous studies have shown the usefulness of the models(Byrne et al., 2016) but have not validated their size and shape. As far as we know, this is the first study to validate the measurements of the three-dimensional model of the airways by radiologists.

Although previous studies have predominantly used the airway diameter to measure structures, we chose to measure the airway perimeter due to the airways' irregular anatomy. This irregularity could have added subjectivity to the measurements had the diameter been used.

We believe that the major contribution of our study is to facilitate development of a three-dimensional model produced entirely locally, in an institution with no prior knowledge in this specific field. We began our journey in the field of three-dimensional printing by joining forces with the Radiology Service, Biomedical Engineering Service, and the Airway Endoscopy Unit of our institution. This approach allowed us to combine the necessary knowledge on image acquisition with post-processing to create the three-dimensional models. The joint teams were fundamental to guiding the efforts that turned the application into a model, which could potentially impact teaching and patient care.

For the development of this prototype, the Radiology Service focused on post-processing of the images (segmentation and creation of the three-dimensional mesh) and evaluating the accuracy of the model dimensions. The Biomedical Engineering Service had the task of correcting the three-dimensional mesh, creating the printing media, printing, and finishing the model. The Airway Endoscopy unit acted as a consultant, evaluating each prototype generated until the final model achieved the subjectively expected levels of finish, color, and malleability of the material.

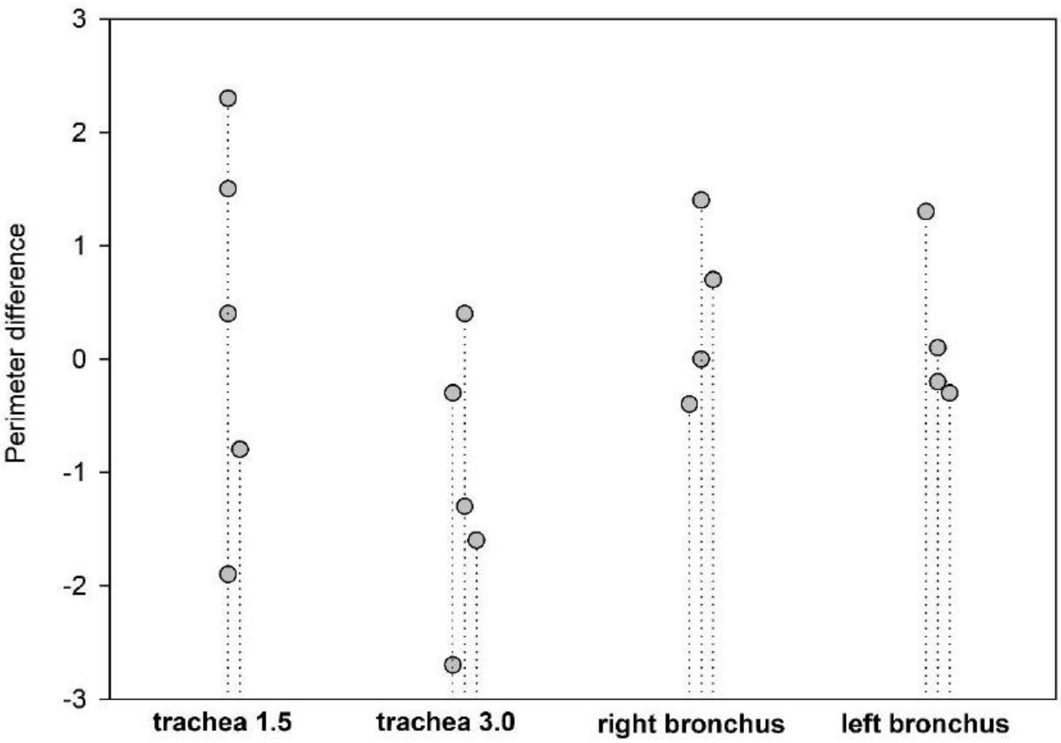
The entire three-dimensional printing process was dominated by researchers. Over several months, approximately 10 models were rejected for obvious flaws. The only step performed outside the institution was the acquisition of a black color acrylic box to accommodate the printed model, with internal dimensions of 205 × 235 × 125 mm (L×H×W) and a wall thickness of 5 mm.

It has been reported that the post-processing stage is most susceptible to distortion of the anatomy and dimensions of structures.(Santana et al., 2012) This susceptibility is higher in the segmentation of non-bone tissues due to the lower attenuation difference between the structure under study and the adjacent tissues. Huotilainen *et al*.(Huotilainen et al., 2014) delegated the printing of the same skull MDCT images to three institutions and compared the dimensions, weight, and number of model triangles. They observed significant differences between the models, including a 1.96-times difference in the volume between the largest and smallest models. The aforementioned study demonstrated the need for quality control in the process of three-dimensional model fabrication and highlighted the discrepancies that the process might inadvertently introduce.

The low correlation observed between the patient and model measurements at each anatomical location might have been due to the small number of observers. When we compared the patient and model together for all the measurements, the correlation was very high. It is also important to note that millimeter differences in airway measurements, such as those observed in our study (maximum difference in trachea circumference: 2.7 mm, 55.4 mm at the patient trachea and 58.1 mm at the printed trachea), may have been due to minimal differences in caliper-positioning on the MDCT images during different reading sessions.

Although it was not an objective of this study, it is interesting to note that the amplitude of the differences measured by the observers decreased at each point (Figure 4), displaying a convergence of the values measured in the left bronchus (last measurement site) in relation to the trachea 1.5 (first measurement site). This may suggest that some amount of learning effect may have occurred in the observers, and that better results may have been obtained, had a pre-test training been performed.

**Figure 4.** Perimeter differences (model vs. patient) at each measurement point for each observer.




Values are in millimeters. Trachea 1.5: Measurement performed in the trachea 1.5 cm proximal to the carina. Trachea 3.0: Measurement performed in the trachea 3.0 cm proximal to the carina. Source: Authors.

Considering the medians obtained at the different points, or even the maximum intra-observer differences, our findings correspond with the differences observed in previous studies involving the printing of soft tissue structures.(George et al., 2017;

Ionita et al., 2014) These studies usually report sub-millimetric differences in the diameter of structures, as demonstrated by Ionita *et al*., who printed models of the Willis polygon.(Ionita et al., 2014)

It is also important to highlight that the differences in magnitude observed in our work (the median differences were equivalent to a maximum of 2% of the median airway caliber) were likely not large enough to be relevant for therapeutic planning or teaching.

Our study has some limitations. These include the small number of evaluators, which may have compromised the results at each measurement site. Further, with the use of just one patient as a model, and only one printer and a single type of tested material, our study cannot guarantee wide reproducibility. Another relevant limitation is that the measurement of accuracy should ideally have been performed by an independent external group.

## 5. Conclusion

In this study, we developed a three-dimensional airway model based on medical images. The differences in the dimensions between the model and the original images corroborated those observed in previous studies and are possibly irrelevant for most applications. In future studies, we plan to evaluate our model as a teaching and learning assessment tool, comparing the training results between this model and models already available in the market.

## References

Akiba, T., Inagaki, T., & Nakada, T. (2014). Three-Dimensional Printing Model of Anomalous Bronchi before Surgery. *Annals of Thoracic and Cardiovascular Surgery*, *20*(Supplement), 659–662. https://doi.org/10.5761/atcs.cr.13-00189

AL-Ramahi, J., Luo, H., Fang, R., Chou, A., Jiang, J., & Kille, T. (2016). Development of an Innovative 3D Printed Rigid Bronchoscopy Training Model. *Annals of Otology, Rhinology & Laryngology*, *125*(12), 965–969. https://doi.org/10.1177/0003489416667742

Barker, T.M., Earwarker, W. J. S., & Lisle, D. A. (1994). Accuracy of stereolithographic models of human anatomy. *Australasian Radiology*, *38*(2), 106–111. https://doi.org/10.1111/j.1440-1673.1994.tb00146.x

Bustamante, S., Bose, S., Bishop, P., Klatte, R., & Norris, F. (2014). Novel Application of Rapid Prototyping for Simulation of Bronchoscopic Anatomy. *Journal of Cardiothoracic and Vascular Anesthesia*, *28*(4), 1122–1125. https://doi.org/10.1053/j.jvca.2013.08.015

Byrne, T., Yong, S. A., & Steinfort, D. P. (2016). Development and Assessment of a Low-Cost 3D-printed Airway Model for Bronchoscopy Simulation Training. *Journal of Bronchology & Interventional Pulmonology*, *23*(3), 251–254. https://doi.org/10.1097/LBR.0000000000000257

Choi, J.-Y., Choi, J.-H., Kim, N.-K., Kim, Y., Lee, J.-K., Kim, M.-K., Lee, J.-H., & Kim, M.-J. (2002). Analysis of errors in medical rapid prototyping models. *International Journal of Oral and Maxillofacial Surgery*, *31*(1), 23–32. https://doi.org/10.1054/ijom.2000.0135

Colt, H. G. (2013). Simulation in bronchoscopy training: are we there yet? *Current Respiratory Care Reports*, *2*(1), 61–68. https://doi.org/10.1007/s13665-012-0033-x

Ernst, A., Wahidi, M. M., Read, C. A., Buckley, J. D., Addrizzo-Harris, D. J., Shah, P. L., Herth, F. J. F., de Hoyos Parra, A., Ornelas, J., Yarmus, L., & Silvestri, G. A. (2015). Adult Bronchoscopy Training: Current state and suggestions for the future. *Chest*, *148*(2), 321–332. https://doi.org/10.1378/chest.14-0678

Frühwald, J., Schicho, K. A., Figl, M., Benesch, T., Watzinger, F., & Kainberger, F. (2008). Accuracy of Craniofacial Measurements. *Journal of Craniofacial Surgery*, *19*(1), 22–26. https://doi.org/10.1097/scs.0b013e318052ff1a

George, E., Liacouras, P., Rybicki, F. J., & Mitsouras, D. (2017). Measuring and Establishing the Accuracy and Reproducibility of 3D Printed Medical Models. *RadioGraphics*, *37*(5), 1424–1450. https://doi.org/10.1148/rg.2017160165

Giannopoulos, A. A., Steigner, M. L., George, E., Barile, M., Hunsaker, A. R., Rybicki, F. J., & Mitsouras, D. (2016). Cardiothoracic Applications of 3-dimensional Printing. *Journal of Thoracic Imaging*, *31*(5), 253–272. https://doi.org/10.1097/RTI.0000000000000217

Hoang, D., Perrault, D., Stevanovic, M., & Ghiassi, A. (2016). Surgical applications of three-dimensional printing: a review of the current literature and how to get started. *Annals of Translational Medicine*, *4*(23), 456–456. https://doi.org/10.21037/atm.2016.12.18

Huotilainen, E., Jaanimets, R., Valášek, J., Marcián, P., Salmi, M., Tuomi, J., Mäkitie, A., & Wolff, J. (2014). Inaccuracies in additive manufactured medical skull models caused by the DICOM to STL conversion process. *Journal of Cranio-Maxillofacial Surgery*, *42*(5), e259–e265. https://doi.org/10.1016/j.jcms.2013.10.001

Ibrahim, D., Broilo, T. L., Heitz, C., de Oliveira, M. G., de Oliveira, H. W., Nobre, S. M. W., dos Santos Filho, J. H. G., & Silva, D. N. (2009). Dimensional error of selective laser sintering, three-dimensional printing and PolyJet™ models in the reproduction of mandibular anatomy. *Journal of Cranio-Maxillofacial Surgery*, *37*(3), 167–173. https://doi.org/10.1016/j.jcms.2008.10.008

Ionita, C. N., Mokin, M., Varble, N., Bednarek, D. R., Xiang, J., Snyder, K. V., Siddiqui, A. H., Levy, E. I., Meng, H., & Rudin, S. (2014). Challenges and limitations of patient-specific vascular phantom fabrication using 3D Polyjet printing. In R. C. Molthen & J. B. Weaver (Eds.), *Proceedings of SPIE--the*

*International Society for Optical Engineering* (Vol. 9038, p. 90380M). Proc SPIE Int Soc Opt Eng. https://doi.org/10.1117/12.2042266

Langridge, B., Momin, S., Coumbe, B., Woin, E., Griffin, M., & Butler, P. (2018). Systematic Review of the Use of 3-Dimensional Printing in Surgical Teaching and Assessment. *Journal of Surgical Education*, *75*(1), 209–221. https://doi.org/10.1016/j.jsurg.2017.06.033

Matsumoto, J. S., Morris, J. M., Foley, T. A., Williamson, E. E., Leng, S., McGee, K. P., Kuhlmann, J. L., Nesberg, L. E., & Vrtiska, T. J. (2015). Three-dimensional Physical Modeling: Applications and Experience at Mayo Clinic. *RadioGraphics*, *35*(7), 1989–2006. https://doi.org/10.1148/rg.2015140260

Mitsouras, D., Liacouras, P., Imanzadeh, A., Giannopoulos, A. A., Cai, T., Kumamaru, K. K., George, E., Wake, N., Caterson, E. J., Pomahac, B., Ho, V. B., Grant, G. T., & Rybicki, F. J. (2015). Medical 3D Printing for the Radiologist. *RadioGraphics*, *35*(7), 1965–1988. https://doi.org/10.1148/rg.2015140320

Miyazaki, T., Yamasaki, N., Tsuchiya, T., Matsumoto, K., Takagi, K., & Nagayasu, T. (2015). Airway Stent Insertion Simulated With a Three-Dimensional Printed Airway Model. *The Annals of Thoracic Surgery*, *99*(1), e21–e23. https://doi.org/10.1016/j.athoracsur.2014.10.021

Parotto, M., Jiansen, J. Q., AboTaiban, A., Ioukhova, S., Agzamov, A., Cooper, R., O'Leary, G., & Meineri, M. (2017). Evaluation of a low-cost, 3D-printed model for bronchoscopy training. *Anestezjologia Intensywna Terapia*, *49*(3), 189–197. https://doi.org/10.5603/AIT.a2017.0035

Pedersen, T. H., Gysin, J., Wegmann, A., Osswald, M., Ott, S. R., Theiler, L., & Greif, R. (2017). A randomised, controlled trial evaluating a low cost, 3D-printed bronchoscopy simulator. *Anaesthesia*, *72*(8), 1005–1009. https://doi.org/10.1111/anae.13951

Petropolis, C., Kozan, D., & Sigurdson, L. (2015). Accuracy of medical models made by consumer-grade fused deposition modelling printers. *Plastic Surgery*, *23*(2). https://doi.org/10.4172/plastic-surgery.1000912

Salmi, M., Paloheimo, K.-S., Tuomi, J., Wolff, J., & Mäkitie, A. (2013). Accuracy of medical models made by additive manufacturing (rapid manufacturing). *Journal of Cranio-Maxillofacial Surgery*, *41*(7), 603–609. https://doi.org/10.1016/j.jcms.2012.11.041

Santana, R. R., Lozada, J., Kleinman, A., Al-Ardah, A., Herford, A., & Chen, J.-W. (2012). Accuracy of Cone Beam Computerized Tomography and a Three-Dimensional Stereolithographic Model in Identifying the Anterior Loop of the Mental Nerve: A Study on Cadavers. *Journal of Oral Implantology*, *38*(6), 668–676. https://doi.org/10.1563/AAID-JOI-D-11-00130

Taft, R. M., Kondor, S., & Grant, G. T. (2011). Accuracy of rapid prototype models for head and neck reconstruction. *The Journal of Prosthetic Dentistry*, *106*(6), 399–408. https://doi.org/10.1016/S0022-3913(11)60154-6

Wu, A.-M., Shao, Z.-X., Wang, J.-S., Yang, X.-D., Weng, W.-Q., Wang, X.-Y., Xu, H.-Z., Chi, Y.-L., & Lin, Z.-K. (2015). The Accuracy of a Method for Printing Three-Dimensional Spinal Models. *PLOS ONE*, *10*(4), e0124291. https://doi.org/10.1371/journal.pone.0124291