THREE-DIMENSIONAL MODELS OF THE TRACHEOBRONCHIAL TREE FOR CLINICAL SIMULATION: FROM TRANSLATIONAL ANATOMY TO RAPID-PROTOTYPING TECHNOLOGY

Pedro Vinicius Porfirio – pedro.porfirio@ufpe.br

Department of Physical Therapy - Federal University of Pernambuco - UFPE

orcid.org/0000-0002-1233-6500

Carlos Alfredo Ramirez Gonzalez - *doctorcgonzalez@gmail.com*

Pernambuco State Health Department - SES-PE/SESAP-Recife

orcid.org/0000-0003-1380-0368

André Pukey Oliveira Galvão – andre.pukey@ufpe.br

Graduate Program in Functional Biology - Federal University of Rio Grande do Norte - UFRN

orcid.org/0000-0002-3914-2255

Paulo Roberto Sá de Oliveira Neto – paulo.roberton@ufpe.br

Department of Electrical Engineering, Federal University of Pernambuco - UFPE

orcid.org/0000-0003-2134-5916

Armele Dornelas de Andrade – armele.andrade@ufpe.br

Graduate Program in Physical Therapy - Federal University of Pernambuco - UFPE

orcid.org/0000-0001-9430-4395

Shirley Lima Campos – shirley.campos@ufpe.br

Graduate Program in Physical Therapy - Federal University of Pernambuco - UFPE

orcid.org/0000-0003-3079-8300

***Abstract*— Objective:** To develop a three-dimensional model of the tracheobronchial tree up to the third generation using additive manufacturing. **Methods:** A methodological study using rapid prototyping. Four dissected porcine lungs were used in the pilot, but due to structural limitations, the process shifted to digital modeling. A tracheobronchial tree model from the Renderhub library (author: "RachidSW") based on pulmonary CT scans was edited, simplified to the third alveolar generation, and 3D printed in polylactic acid with an epoxy resin coating for impermeability. **Results:** The pilot experiments produced a solid porcine tracheobronchial tree model, showing resolution loss at the tracheal level and lacking a hollow lumen. A human-based model was then 3D-printed in solid white (270 × 266 × 300 mm) with high accuracy (mean deviation 0.2 mm) and structural features suitable for educational purposes. Following manual support removal and waterproofing, the model was functional in simulation experiments, with a reduced cost of 16 USD per piece. **Conclusion:** The developed 3D tracheobronchial tree model enables safe, hands-on learning of respiratory anatomy and supports healthcare training. Future studies should incorporate distal airways, lumen structures, and tissue-mimicking materials, as well as validate the models against cadaveric, animal, and commercial references to enhance their educational and clinical applicability.

***Keywords*—** airway management, three-dimensional printing, additive manufacturing, translational research.

1 INTRODUCTION

Clinical simulation has been increasingly recognized as a strategy for teaching and enhancing clinical skills (1). Compared with traditional methods, simulation-based training offers advantages that support reproducibility without ethical constraints (2). Complementing this approach, rapid-prototyping technology (three-dimensional printing) has been applied in healthcare, with growing evidence demonstrating its value as a practical tool for training and education (3–5).

The respiratory system, and particularly the tracheobronchial tree, stands out for its anatomical complexity and clinical relevance in procedures such as intubation, diagnostic and therapeutic bronchoscopy, aspiration, and the management of difficult airways (3,6–8). The currently available models, whether cadaveric or synthetic replicas, present important limitations in terms of anatomical fidelity, cost, and availability (6). These constraints highlight the need for innovative solutions that integrate anatomical accuracy with clinical applicability, thereby expanding the opportunities for training.

In addition to cadaveric and synthetic models, animal models have played a relevant role in translational research, particularly in the respiratory field. The anatomical similarity of the porcine lung to that of humans has established it as an important bridge between experimental studies and clinical practice, contributing to research on cystic fibrosis, coronavirus, pneumonia, ventilator-induced lung injury (9–12), as well as applications in anesthesia, transplantation, and interventional bronchoscopy (13–17). However, ethical concerns, challenges related to specimen preservation and disposal, and the shortage of donors limit their broader use (18). In this context, additive manufacturing offers a promising alternative, enabling the development of three-dimensional prototypes with high anatomical fidelity, greater accessibility, and broad applicability in clinical training, surgical planning, and research.

Recent advances in medical imaging, computational modeling, and additive manufacturing have helped to overcome these barriers. Open-source magnetic resonance or computed tomography (CT) imaging databases allow three-dimensional reconstructions of specific anatomical structures, while 3D-printing techniques enable their materialization into physical models with anatomical properties (3). This technological convergence supports the development of models that enhance the understanding of anatomy and physiology, facilitate clinical training and surgical planning, and guide interventions (18,19).

The integration of CT-derived anatomical models with additive manufacturing further expands opportunities in education, applied research, procedural planning, and the development of new medical technologies. Accordingly, this methodological study aims to describe the development of a three-dimensional tracheobronchial tree model using additive manufacturing.

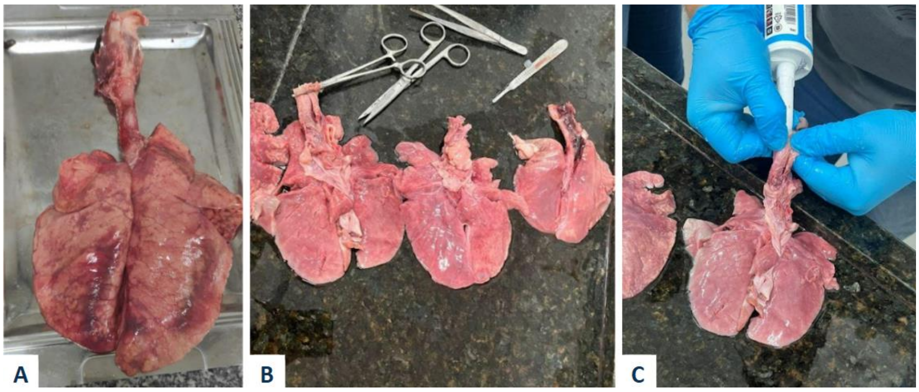
2 METHODS

This descriptive, methodological study, based on rapid prototyping, was conducted at the Multiuser Laboratory of Instrumental Innovation and Physical-Functional Performance (LINDEF-UFPE), and followed the framework proposed by Mbuagbaw et al. (20) for methodological research in healthcare.

Pilot development in a porcine model

For the initial execution of the techniques, four dissected porcine lungs were used (Figure 1), comprising ten lobar bronchi on each side. The specimens were provided by collaborating researchers from the LINDEF and were carefully inspected to exclude lesions that could compromise the procedure or lead to leakage of the injected solution.

Figure 1. Pig lung models used for resin filling. (A) Removal of the organ; (B) Dissection and removal of adjacent tissues; (C) Injection of resin.



Source: produced by the authors.

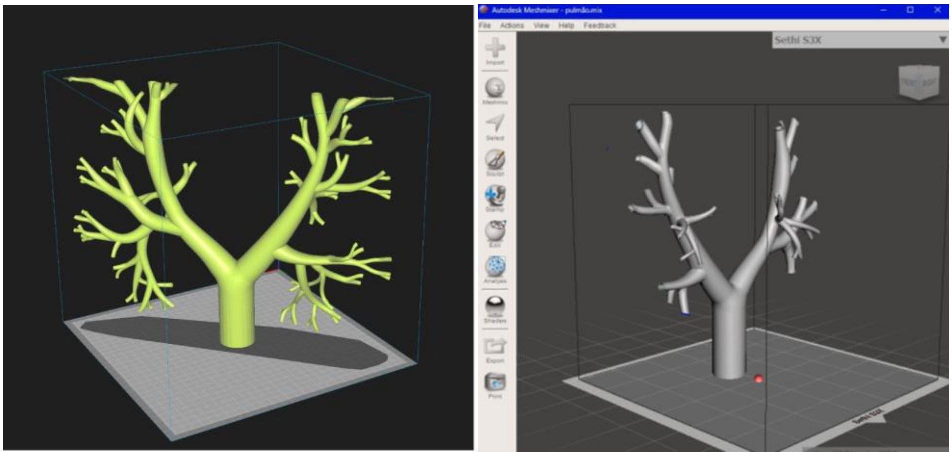
After dissection and removal of adjacent tissues, flexible resin (RQ-0120), rigid resin (R1-0110), and silicone rubber were injected into different specimens. Subsequently, an additional coating of epoxy resin (MV ORG IBX; IBEX, Pernambuco, Brazil) was applied to enhance structural resistance and impermeability. Once the materials solidified, the specimens were immersed in an acid solution to corrode the surrounding lung tissue and expose the casts. However, we observed that the injected compounds were also susceptible to corrosion, which compromised the anatomical structures. As an alternative, the process was redirected towards rapid-prototyping technology.

Three-dimensional model design and processing

To develop the full-scale three-dimensional model, a digital file derived from medical images available in the Harvard University database (chestimagingplatform.org) was used. The original model (385 × 385 × 50 mm, extending to the sixth alveolar generation) was segmented and simplified to the third bronchial generation using MeshMixer (Autodesk, USA), with additional adjustments performed in Cinema 4D (Maxon, Germany).

The final digital model was sliced in Ultimaker Cura 2.1.1 (Netherlands) with a layer thickness of 0.28 mm and printed on a SETHI S3X 3D printer (Recife, Brazil) using polylactic acid (PLA) filament (Voolt 3D, 1.75 mm, off-white) (Figure 2). Printing conditions included a bed temperature of 60 °C, a print speed of 70 mm/s, and 100% infill. To prevent interlamellar leakage, which is characteristic of FDM/FFF technology, the prototype was coated with flexible resin RQ-0120.

Figure 2. Bronchial tree model completed for three-dimensional printing.



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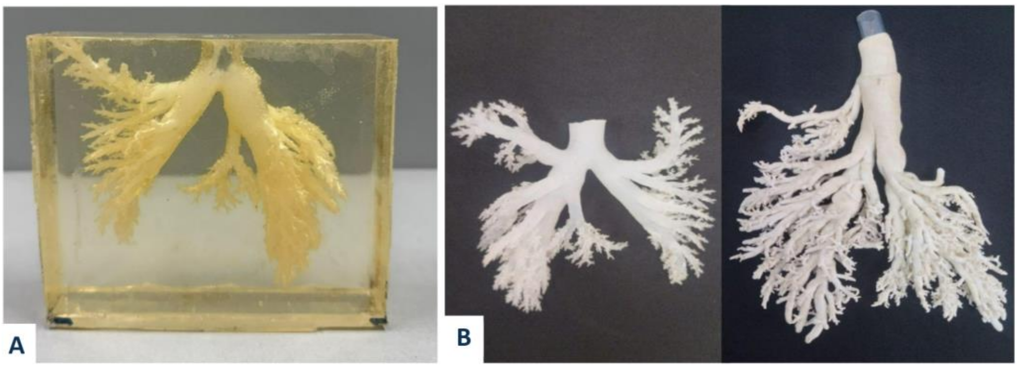
3 RESULTS AND DISCUSSION

The outcomes of the pilot experiments are presented in Figure 3 (A and B). In Figure 3A, a solid porcine tracheobronchial tree model is shown, displaying some resolution loss at the tracheal level but adequate filling of the more distal bronchi. This model was subsequently refined, resulting in the improved representation depicted in Figure 3B, which illustrates a 3D reconstruction of 23 bronchial generations coated with silicone, however, still without lumen or hollow inner diameter.

Figure 3. (A) Solid porcine tracheobronchial tree model coated with silicone; (B) three-dimensional reconstruction with 23 bronchial generations.



Source: produced by the authors.

In the progression toward a human model based on CT analyses, a final tracheobronchial tree model was 3D-printed in solid white, measuring 270 × 266 × 300 mm, demonstrating high accuracy with a mean deviation of 0.2 mm. The prototype exhibited porosity features and the presence of internal and external supports (Figure 5), rendering it suitable for educational applications.

Figure 5. Final tracheobronchial tree model, comprising 10 segments per hemithorax.

Source: produced by the authors.

For instrumental use, manual adjustments were performed, including the removal of filament supports with a micro-grinder and the waterproofing of the model using a specialized resin. After these refinements, the model proved suitable and is currently employed in experiments and simulation tests, with a reduced cost of 16 USD per piece.

In this translational study, we developed a low-cost three-dimensional model of the tracheobronchial tree using rapid-prototyping technology, as an alternative to cadaveric, synthetic, or animal-based models. Our results demonstrate the feasibility of developing anatomically accurate models using additive manufacturing, bridging the gap between experimental research with animal models and clinical simulation.

Despite the notable anatomical and physiological similarities of the porcine lung to its human counterpart, important species-specific differences must be considered, including the configuration of intrathoracic organs, rib cage morphology, and chest wall mechanics (21). Furthermore, the human tracheobronchial tree predominantly exhibits a bipodial pattern, whereas the porcine tree follows a monopodial design, with each main bronchus generating smaller side branches at obtuse angles (22,23). These anatomical distinctions underscore the importance of anatomically precise models, such as ours, particularly for investigating airway physiology and mucus flow, where accurate representation of branching geometry and airway dimensions is essential for reliable experimental outcomes and translational relevance.

Additive manufacturing enables the creation of physical objects through the successive layering of material, in contrast to traditional subtractive fabrication methods, and has been widely applied in healthcare (24). This technology allowed for high precision and customization of the anatomical model, enhancing access to innovative educational resources for students and healthcare professionals. Previous studies indicate that 3D models improve student understanding, promote greater skill and competence in respiratory morphofunctionality, and increase safety in simulated clinical scenarios (4,5).

Most studies report that 3D printing technologies are cost-effective; however, many do not provide detailed data on material or operational costs for model production (25–28). The results of the present research demonstrate that 3D printing is indeed a cost-effective method for producing anatomical models, though several factors must be considered when evaluating costs, such as the source of the digital model and its complexity. Costs are lowest when digital models are available from public sources in stl. or obj. format, whereas models requiring CAD design become significantly more expensive due to personnel and operational expenses (29). In our case, the relatively simple tracheobronchial tree model was produced at only 16 USD, benefiting from minimal material use and limited post-processing, illustrating how model complexity directly influences production cost.

Limitations

The present model is limited by its anatomical simplification to the third bronchial generation, the inability of printed materials to replicate tissue-like mechanical properties, and the reliance on manual post-processing, which may reduce reproducibility. In addition, validation was restricted to pilot applications, without systematic comparison to cadaveric, animal, or commercial alternatives.

4 CONCLUSIONS

The three-dimensional model of the tracheobronchial tree developed enables hands-on learning and familiarization with respiratory anatomy in a safe and reproducible manner, contributing to the training of healthcare professionals. The use of 3D-printed models provides opportunities to enhance anatomical knowledge, develop clinical skills, and consolidate practical experience, positioning this technology as an innovative and strategic tool in healthcare education and training. Future studies should aim to address current limitations by incorporating distal airway generations, lumen structures, and tissue-mimicking materials, as well as performing systematic validation against cadaveric, animal, and commercial models to expand their clinical and educational applicability.

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