International Journal of Clinical Medicine, 2025, 16(10), 395-402
https://www.scirp.org/journal/ijcm
ISSN Online: 2158-2882
ISSN Print: 2158-284X

Improved Generation-Specific Airway Patency in 3D Printed Models through Layer and Exposure Time Modifications

Emmanuele Fale[1], Jaskiran Khosa[2], Roy Joseph Cho[2]*

[1]University of Minnesota Medical School, Minneapolis, USA
[2]Section of Interventional Pulmonology, University of Minnesota Medical School, Minneapolis, USA
Email: *choxx548@umn.edu

How to cite this paper: Fale, E., Khosa, J. and Cho, R.J. (2025) Improved Generation-Specific Airway Patency in 3D Printed Models through Layer and Exposure Time Modifications. *International Journal of Clinical Medicine*, **16**, 395-402.
https://doi.org/10.4236/ijcm.2025.1610027

Received: August 27, 2025
Accepted: September 27, 2025
Published: September 30, 2025

Abstract

Three-dimensional (3D) printing offers transformative potential for interventional pulmonology by enabling patient-specific models for simulation, surgical planning, and device development. However, accurate reproduction of the multi-generational airway tree remains limited by printing artifacts and lumen distortion, particularly in resin-based methods. This pilot study evaluated whether modifying resin printing parameters could improve airway patency and anatomical fidelity. Twenty identical human airway models were fabricated with an Elegoo Saturn 8K printer: ten with default manufacturer settings and ten with a modified protocol incorporating reduced layer height, fewer bottom layers, shortened standard exposure time, and prolonged bottom-layer exposure. Bronchoscopic inspection revealed that default settings produced incomplete carinas and collapsed second- and third-generation bronchi, whereas the modified protocol yielded smoother lumens, sharply defined carinas, and continuous branching to third-generation airways. Quantitative scoring confirmed reduced surface artifacts and greater branch continuity in the modified group. These findings demonstrate that tailored resin printing parameters enhance fidelity and functional utility of airway models. Such improvements support applications in high-fidelity training, preoperative planning, patient-specific device design, and computational studies. Parameter optimization may expand the translational role of 3D printing in pulmonary medicine by ensuring models are not only visually accurate but also dynamically functional.

Keywords

3D Printing, Airway Models, Bronchoscopy Simulation, Resin Printing Optimization, Interventional Pulmonology

1. Introduction

Three-dimensional (3D) printing has emerged over the past decade as one of the most transformative technologies in the biomedical sciences, providing an unprecedented opportunity to fabricate physical replicas of complex anatomical structures. This capability is especially valuable in specialties such as interventional pulmonology, where the ability to accurately visualize, manipulate, and rehearse procedures within patient-specific airway anatomy can have a direct impact on safety and clinical outcomes. Traditional imaging modalities such as computed tomography (CT) and magnetic resonance imaging (MRI) provide detailed information in two dimensions, but they often fail to capture the full spatial complexity of branching airways. A three-dimensional model created from imaging data can bridge this gap by offering tactile and visual feedback [1] in ways that no digital display or two-dimensional cross-sectional image can replicate.

The application of 3D printing to airway modeling has particular significance given the challenges associated with navigating, diagnosing, and treating lesions within the bronchial tree. Airways progressively taper and branch at varying angles, creating a highly complex network [2] that is prone to collapse and distortion in physical models. Clinicians who perform bronchoscopy, stent placement, tumor resection, or complex airway reconstructions benefit from being able to study patient-specific airway models in advance of a procedure. In educational settings, residents and fellows can rehearse high-risk maneuvers in a safe environment before ever attempting them on patients. For device developers, 3D printed airways provide a reproducible platform to evaluate the performance of new catheters, stents, or robotic navigation systems.

Despite these advantages, the fidelity of airway models produced by 3D printers has historically been variable. Fused deposition modeling (FDM) printers, which extrude thermoplastic material layer by layer, have been widely available and inexpensive. However, their resolution is limited by the diameter of the extrusion nozzle and the thickness of each layer, leading to visible "stair stepping" artifacts and luminal distortions. For airway structures, which often measure only a few millimeters in diameter, these limitations can compromise the accuracy of bifurcations and distal segments. Resin-based printers, including stereolithography (SLA) and digital light processing (DLP) devices, address some of these shortcomings by using light to polymerize liquid resin, achieving finer resolution and smoother surfaces. Yet, resin printing is not without its challenges. Overcuring, distortion of narrow lumens [3], and collapse of delicate branching structures remain common problems, particularly when using default manufacturer settings that are not optimized for complex anatomical geometries.

Recognizing these limitations, our team sought to systematically evaluate whether careful adjustment of resin printer parameters could enhance the patency and fidelity of multi-generational airway models. We hypothesized that modifications aimed at balancing layer resolution, curing time, and adhesion strength would produce airway replicas with sharper carinas, smoother lumens, and continuous branching through at least the third generation of bronchi. To test this hypothesis, we designed a pilot study in which identical airway models were fabricated under two conditions: default manufacturer settings and a modified protocol incorporating reduced layer height, fewer bottom layers, shorter exposure times for standard layers, and prolonged exposure for the initial bottom layers.

2. Methods

2.1. Model Acquisition and Preparation

The source airway geometry was derived from a high-resolution computed tomography scan of an adult human chest. The dataset was segmented using open-source software to isolate the trachea and bronchial tree [4]. The resulting surface file was converted into a stereolithography (STL) format, which served as the blueprint for printing. Particular care was taken during segmentation to preserve second- and third-generation branches, as these are the region's most prone to collapse or occlusion during the printing process.

2.2. Printing Hardware and Resin

All models were fabricated using an Elegoo Saturn 8K resin printer (Elegoo Inc., Shenzhen, China). This printer employs masked stereolithography (MSLA) technology, which uses an array of light-emitting diodes beneath an LCD screen to selectively cure photopolymer resin [5]. The resin selected was a standard clear photopolymer, chosen to allow internal visualization of lumen patency during bronchoscopy.

2.3. Experimental Groups

Twenty identical airway models were produced. Ten were printed using the default settings recommended by the manufacturer, which included a layer height of 0.05 mm, a bottom-layer count of eight, a bottom exposure time of 40 seconds, and a standard exposure time of 2.5 seconds. The other ten were printed using our modified protocol: layer height reduced to 0.025 mm, bottom-layer count reduced to four, bottom exposure time increased to 60 seconds, and standard exposure time shortened to 1.5 seconds. These adjustments were based on preliminary trials suggesting that thinner layers and shorter exposure times minimized overcuring, while longer bottom exposures improved model adhesion and reduced failure rates.

2.4. Post-Processing

Upon completion of printing, models were rinsed in isopropyl alcohol to remove uncured resin, followed by a secondary cure under ultraviolet light. Each model was inspected for gross defects such as warping, fractures, or incomplete builds. No additional mechanical reinforcement was applied, allowing us to evaluate the inherent fidelity of the print parameters alone.

2.5. Bronchoscopic Evaluation

Flexible bronchoscopy was performed using a standard adult bronchoscope with an outer diameter of 5.9 mm. Models were examined systematically from the trachea through successive bronchial generations. Observations were recorded regarding lumen patency, carinal sharpness, and continuity of branching. Still images and videos were captured to document findings.

2.6. Quantitative Scoring

To provide a standardized assessment, two independent observers scored each model on a three-point scale for three criteria: 1) surface smoothness, 2) completeness of carinas, and 3) continuity of branching to the third generation. Each parameter was graded on a three-point ordinal scale, where “1” indicated poor quality (rough or irregular surfaces, blunted or incomplete carinas, or discontinuous/collapsed branches), “2” indicated moderate quality (partially smooth surfaces, partially defined carinas, or partial but incomplete branch continuity), and “3” indicated high quality (smooth luminal surfaces, sharply defined carinas, and continuous patent branches to the third generation). Discrepancies between observers were resolved by consensus. Scores were averaged within each group for comparison. A Mann-Whitney U test was performed on the three-point scoring data (default vs modified protocol).

3. Results

3.1. Gross Inspection

All 20 models were successfully printed and survived post-processing (see **Figure 1**). Grossly, both groups appeared to accurately replicate the tracheobronchial tree, with no obvious external differences. The branching architecture was preserved to the third generation in both groups, but luminal fidelity could not be fully assessed without bronchoscopy.

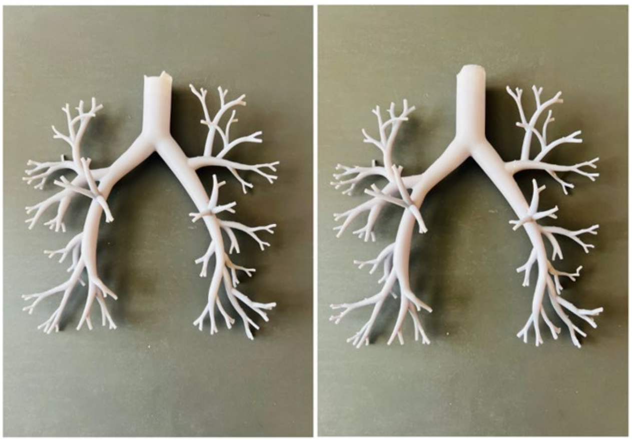
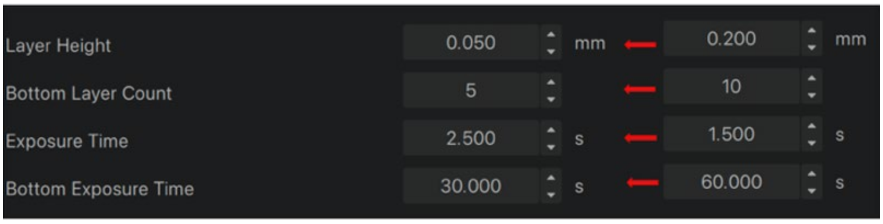


Figure 1. 3D resin printout of a tracheobronchial tree using default (left) and modified (right) settings. Although there are subtle differences, no significant external differences were noted with regard to print quality.

3.2. Bronchoscopic Findings

The default settings group demonstrated significant deficiencies (see **Figure 2** and **Figure 3**). The trachea and mainstem bronchi were patent, but distal branches exhibited partial collapse and narrowing. Carinas between the mainstem and lobar bronchi were often incompletely formed, appearing rounded or blunted rather than sharply bifurcated. In several models, the lumens of second-generation bronchi were obstructed by resin overcuring, creating impassable segments.



Layer Height	0.050	mm	⟵	0.200	mm
Bottom Layer Count	5		⟵	10	
Exposure Time	2.500	s	⟵	1.500	s
Bottom Exposure Time	30.000	s	⟵	60.000	s

Figure 2. Resin printer specific parameters comparing default (right) to modified (left) settings. Reducing layer height, bottom layer count, bottom exposure time and increasing the exposure time improved deformities and patency for 2nd - 3rd generation airways.

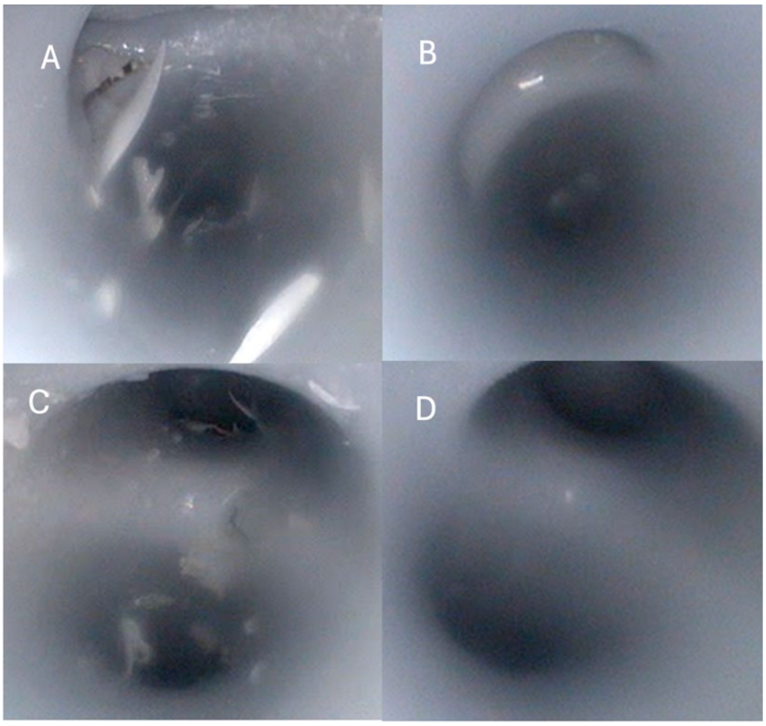


Figure 3. Comparison between default (left) and modified (right) resin printer settings. (A) and (B) represent a distal left mainstem airway with an airway take-off. In comparison, the modified (B) settings allowed for a smooth airway transition in addition to sharp carina. The deformities and absence of the segmental take-off in (A) were due to higher layer counts in addition to less exposure time. (C) and (D) represent a distal right mainstem airway with an airway take-off. The deformities and loss of a sharp carina in (C) were improved with our modified settings, as seen in (D).

In contrast, the modified protocol group showed clear improvements. Lumens were smoother, with fewer protrusions or roughened surfaces. Carinas were sharply delineated, with crisp angles that mirrored human anatomy. Importantly, second- and third-generation branches remained patent, allowing the bronchoscope to pass without obstruction. The improved patency extended not only through the larger bronchi but also into several subsegmental branches, suggesting that the protocol reduced distortion throughout the model.

3.3. Quantitative Scoring

On the three-point scale, default models averaged 1.4 for surface smoothness, 1.6 for carinal completeness, and 1.2 for branch continuity. Modified models scored significantly higher, averaging 2.6 ($U = 0.0$, $p < 0.001$), 2.7 ($U = 1.0$, $p < 0.001$), and 2.5 ($U = 0.0$, $p < 0.01$), respectively. Inter-observer agreement exceeded 90%.

3.4. Representative Images

Figures captured during bronchoscopy illustrated the contrast between the two groups. Images from default models revealed occluded lumens and collapsed branches, whereas modified models displayed open, continuous pathways with sharp anatomic landmarks.

4. Discussion

This study demonstrates that modest adjustments to resin printing parameters can significantly improve the fidelity of 3D printed airway models. The modifications we employed—reduced layer thickness, fewer bottom layers, shortened standard exposures, and prolonged bottom exposures—collectively enhanced both the visual and functional qualities of the models. The improvements were not superficial; they translated into meaningful gains in lumen patency, carinal definition, and branch continuity, which are precisely the features most critical for bronchoscopy simulation and device evaluation.

These findings align with prior reports highlighting the sensitivity of resin printing outcomes to parameter selection. Martelli and colleagues, in a systematic review of 3D printing in surgery, noted that accuracy is frequently compromised when default manufacturer settings are used without adaptation to specific anatomical geometries. Similarly, He *et al.* [5] demonstrated that parameter optimization improves surface quality and geometric precision in soft tissue prostheses. Our results extend these observations to airway modeling, showing that even small changes in curing time or layer thickness can have a profound impact on distal airway fidelity.

From a translational perspective, the implications are substantial [6]. For medical education, high-fidelity airway models can revolutionize bronchoscopy training. Unlike cadaveric specimens, which are costly, perishable, and variably available, 3D printed models are reproducible, customizable, and relatively inexpensive. They can be generated directly from patient imaging, allowing trainees to rehearse procedures on anatomy that mirrors their clinical cases. For practicing interventional pulmonologists, such models can facilitate preoperative planning for complex resections or stent placements, reducing uncertainty and operative time.

Beyond training, computational fluid dynamics represents another promising application [7]. Accurate airway geometries are essential for modeling airflow patterns, resistance, and gas exchange. Distorted or collapsed branches introduce artifacts that compromise the validity of simulations. Our modified printing protocol ensures that lumen diameters and branching angles are preserved, supporting the development of more realistic computational models.

In device development, 3D printed airway models serve as valuable test platforms for new stents, catheters, or robotic navigation systems. The ability to rapidly print anatomically faithful replicas allows engineers and clinicians to identify design flaws before moving to animal or human testing, thereby reducing costs and accelerating innovation. The improvements in patency and continuity demonstrated here directly enhance the utility of such models for this purpose.

Despite these strengths, our study has limitations. The sample size was modest, and quantitative scoring relied on subjective assessments, albeit with high inter-observer agreement. We did not perform dimensional analysis against the original CT data to confirm absolute geometric accuracy. Future studies should integrate imaging-based validation and expand to larger, more diverse airway geometries, including pediatric and pathologic cases. Additionally, while our modified protocol improved lumen fidelity, it may not represent the optimal settings for all printers or resins. Further research is needed to generalize these findings across different hardware and materials. Another limitation is that our models were rigid due to the nature of cured resin [8]. While rigidity supports structural fidelity, it does not replicate the dynamic compliance of human airways. Emerging flexible resins may provide an avenue to combine geometric accuracy with biomechanical realism, further enhancing the training and simulation value of 3D printed models.

Looking forward, the integration of CT-derived models with intraoperative imaging and computational analysis could establish a comprehensive workflow in which patient-specific airway models are generated within hours of imaging. This would allow clinicians to rehearse complex interventions on the very anatomy they will encounter in the operating room. Coupling optimized printing protocols with flexible resins and advanced segmentation techniques could yield models that are not only anatomically accurate but also physiologically relevant.

In conclusion, our pilot study highlights the critical importance of parameter optimization in resin-based 3D printing of airway models. By adjusting layer height, bottom-layer count, and exposure times, we achieved significant improvements in lumen patency, carinal sharpness, and branch continuity. These refinements have direct applications in education, surgical planning, computational modeling, and device development. As 3D printing becomes increasingly integrated into interventional pulmonology, continued optimization will be essential to ensure that models are both visually accurate and dynamically functional.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Vaezi, M., Seitz, H. and Yang, S. (2012) A Review on 3D Micro-Additive Manufacturing Technologies. *The International Journal of Advanced Manufacturing Technology*, **67**, 1721-1754. https://doi.org/10.1007/s00170-012-4605-2

[2] Klein, G.T., Lu, Y. and Wang, M.Y. (2018) 3D Printing and Neurosurgery-Ready for Prime Time? *World Neurosurgery*, **109**, 153-157.

[3] Choi, J.W., Kim, G., Hong, S., An, J.H., Kim, B. and Ha, C.W. (2022) Sequential Process Optimization for a Digital Light Processing System to Minimize Trial and Error. *Scientific Reports*, **12**, Article No. 13553. https://doi.org/10.1038/s41598-022-17841-5

[4] Martelli, N., Serrano, C., van den Brink, H., Pineau, J., Prognon, P., Borget, I., *et al.* (2016) Advantages and Disadvantages of 3-Dimensional Printing in Surgery: A Systematic Review. *Surgery*, **159**, 1485-1500. https://doi.org/10.1016/j.surg.2015.12.017

[5] He, Y., Xue, G.H. and Fu, J.Z. (2014) Fabrication of Low-Cost Soft Tissue Prostheses with the Desktop 3D Printer. *Scientific Reports*, **4**, Article No. 6973. https://doi.org/10.1038/srep06973

[6] Tumbleston, J.R., Shirvanyants, D., Ermoshkin, N., Janusziewicz, R., Johnson, A.R., Kelly, D., *et al.* (2015) Continuous Liquid Interface Production of 3D Objects. *Science*, **347**, 1349-1352. https://doi.org/10.1126/science.aaa2397

[7] Ventola, C.L. (2014) Medical Applications for 3D Printing: Current and Projected Uses. *P&T: A Peer-Reviewed Journal for Formulary Management*, **39**, 704-711.

[8] Morrison, R.J., Hollister, S.J., Niedner, M.F., Mahani, M.G., Park, A.H., Mehta, D.K., *et al.* (2020) Mitigation of Tracheobronchomalacia with 3D-Printed Personalized Medical Devices in Pediatric Patients. *Science Translational Medicine*, **12**, eaaw6934.