ORIGINAL RESEARCH

Incorporating a Three-Dimensional Printed Airway into a Pediatric Flexible Bronchoscopy Curriculum

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ABSTRACT

Background: Although hands-on simulation plays a valuable role in procedural training, there are limited tools available to teach pediatric flexible bronchoscopy (PFB). Fellowship programs rely on patient encounters, with inherent risk, or high-cost virtual reality simulators that may not be widely available and create education inequalities.

Objective: Our objective was to study the educational value and transferability of a novel, low-cost, three-dimensional-printed pediatric airway model (3D-AM) for PFB training. Our central hypothesis was that the 3D-AM would have high educational value and would be easily transferrable to learners at different teaching hospitals.

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Methods: The 3D-AM was designed to teach technical bronchoscopy skills, airway anatomy, airway pathology, and bronchoalveolar lavage (BAL). The curriculum was offered to incoming fellows in pediatric pulmonology, pediatric surgery, and pediatric critical care across three different teaching institutions. After course completion, each participant assessed the simulation model(s) with a 5-point Likert scale across six domains: physical attributes, realism of experience, ability to perform tasks, value, relevance, and global impression. The expert instructors assessed the learners' competency using a modified version of the Bronchoscopy Skills and Tasks Assessment Tool.

Results: A total of 14 incoming fellows participated in the course. The mean scores for the 3D-AM across all six domains and across the three institutions was between 4 and 5, suggesting that learners generally had a favorable impression and a similar experience across different institutions. All learners "agreed" or "strongly agreed" that the course was a valuable use of their time, helped teach technical skills and airway anatomy, and would be useful for extra training during fellowship. Most of the learners correctly identified anatomy, bronchomalacia, and performed a BAL. Wall trauma was observed in 36% of learners.

Conclusion: The utility, low cost, and transferability of this model may create opportunities for PFB training across different institutions despite resource limitations in the United States and abroad.

Keywords:
simulation; endoscopy; procedural training

Pediatric bronchoscopists must have extensive knowledge of tracheobronchial airway anatomy and sufficient exposure to hands-on training to optimize diagnostic and therapeutic capabilities. However, pediatric flexible bronchoscopy (PFB) training opportunities for pediatric pulmonology (PP), pediatric critical care (PCC), and pediatric surgery (PS) fellows have been limited by reduced numbers of procedures due to the coronavirus disease (COVID-19) pandemic, lack of standardized training programs, and inadequate simulation models for training (1). Although procedure numbers have started to recover since the end of the pandemic, simulation models are needed to ensure appropriate training when actual patient procedure numbers are insufficient. According to a survey of program directors in 2014, teaching approaches varied and included mostly direct patient care (2). The American Thoracic Society recommends a list of core competencies for expert pediatric bronchoscopists (3). These include didactic knowledge (including the indications and contraindications of the procedure), the ability to optimize safety and minimize risk, technical skills of bronchoscopy and bronchoalveolar lavage (BAL), and recognizing specific airway pathology. However, there are no standardized tools to guide training. Virtual reality simulators, although a valuable way to improve knowledge of anatomy, are not a feasible option at smaller institutions without access to high-cost simulation equipment (4). Disparities in teaching resources risk creating educational inequalities.

Additive manufacturing, or the use of computer-aided design and three-dimensional (3D) printing, has provided an opportunity to design realistic and durable surgical models for medical education. Compared with traditional virtual reality simulators, low-fidelity 3D-printed airways have been shown to be more affordable and more realistic and to provide better haptic feedback (5–7). 3D-printed simulation models can be produced rapidly, are relatively low cost, and can be easily transported, creating numerous possibilities for surgical simulation models, particularly at underresourced institutions (5, 7–10). 3D-printed airway models, including those that simulate various airway pathologies, have been found to be realistic, useful, and affordable when used for adult flexible bronchoscopy training (6, 7, 10–14); however, there is limited experience using 3D airway models in pediatric bronchoscopy training (15–17). Pediatric flexible bronchoscopy requires the use of smaller bronchoscopes, cameras, suction ports, and fluid aliquots for BAL. Furthermore, pathologies, such as congenital bronchomalacia, and heightened risks of bronchospasm and lumen trauma, make PFB distinct from adult flexible bronchoscopy.

The objective of this study was to examine the educational value and external validity of a novel 3D-printed pediatric airway model (3D-AM) in PFB training. We hypothesized that a 3D-printed airway would have high educational value and would be easily transferrable across different teaching hospitals.

METHODS

Study Population

Learners included first-year PS, PCCM, and PP fellows at the University of Michigan and PP fellows at Indiana University and Washington University in Saint Louis. The teaching curriculum took place within the first 2 months of fellowship at each institution.

Simulator Development

To design an anatomically accurate 3D-AM, a deidentified computed tomography scan of representative pediatric lungs was converted into a 3D digital model using the segmentation software Materialise Mimics as previously described (8, 9). Using computer-aided design software, this digital model was modified to include only the relevant airway anatomy from the vocal cords to the third-generation bronchi and further optimized to facilitate 3D printing. The model was built with an elastic engineering resin with Shore 50A durometer from Formlabs using stereolithography 3D printing, which cures liquid resin into a formed structure using ultraviolet light (Figure 1A). Several iterations of alternative materials were trialed. More rigid materials caused greater resistance when navigating with a bronchoscope. A wall thickness of 2 mm offered a suitable balance of compressibility and durability. The external airway surface was colored to replicate the anatomic tone of the airway lumen. A benchtop opaque housing was designed to position the airway at a 15-degree angle, simulate a 7-mm lumen to insert the bronchoscope and visualize the vocal cords, and conceal the bronchoscope location in the airway. Threaded external pegs were incorporated into the body of the housing so that airway compression could be applied to simulate obstructive airway lesions, such as vascular compression and tracheobronchomalacia (Figures 1B and 1C). Our specific model was printed using the Ultimaker 3D printer. Production of one model had material costs of $54.04. Generic materials would have cost an estimated $23.21. Print

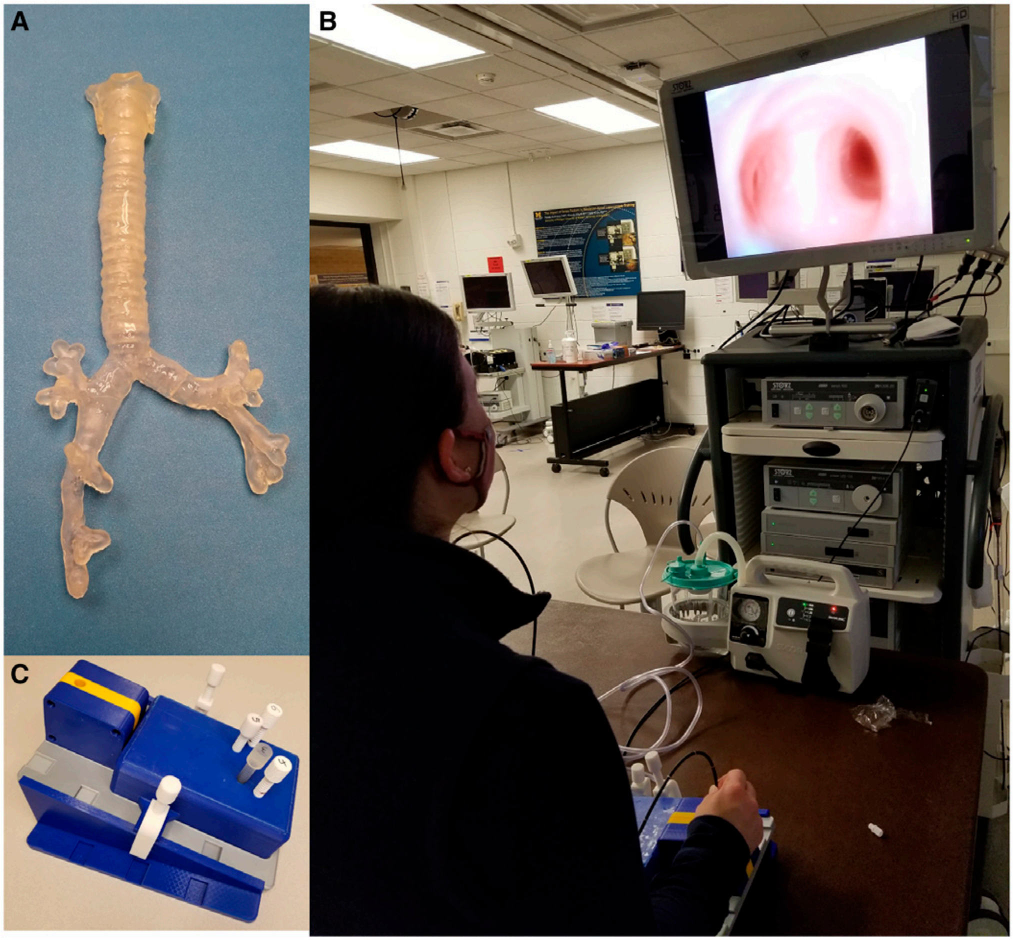

Figure 1. (*A*) Airway model outside of housing demonstrating a small reservoir in the right lower lobe bronchus for simulation of bronchoalveolar lavage. (*B*) Learner performing a bronchoscopy simulating left mainstem bronchomalacia. (*C*) Airway model housing including external pegs designed to simulate airway compression when screwed clockwise.

time was 60 hours and 45 minutes, with an additional day for postproduction processing and assembly. The realism of the models was validated by expert bronchoscopists before implementation of the training curriculum.

Curriculum Description

The teaching curriculum included a 12-minute didactic video and hands-on training with the 3D-AM. The 12-minute video provided instructions on the indications, contraindications, and risks of bronchoscopy, infection control measures, equipment review, technical instruction, operating room management, airway management, anesthesia, and airway anatomy. The course content is based on the American Thoracic Society recommendations for PFB competencies. Didactic bronchoscopy teaching was expanded at each institution by expert instructors according to the unique local practices and resources. Learners were given one-on-one instruction by expert bronchoscopists (all pediatric pulmonologists) over 1 hour to learn technical skills, normal anatomy, how to identify tracheobronchomalacia, and how to perform BAL. One expert instructor was assigned at each center to teach and assess the learners. Expert instructors discussed the course in detail in advance in a number of virtual meetings to review the details of the model and agree on a common approach to teaching.

Assessment Tools

Before the curriculum, nine expert bronchoscopists from various procedural subspecialties (PP, PCC medicine, pediatric anesthesia) performed a simulation bronchoscopy using the 3D-AM and tested the simulated scenarios (identification of airway compression and performance of a BAL). The operators assessed the model using a 5-point Likert scale across six domains: physical attributes, realism of experience, ability to perform tasks, value, relevance, and global assessment (*see* data supplement) (18). After completion of the curriculum, learners assessed: *1*) the 3D-AM using the same assessment instrument used by expert bronchoscopist validators; and *2*) the course overall. Statements regarding the course were addressed using a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Expert instructors observed each learner perform a bronchoscopy using the 3D-AM, identify anatomic landmarks and tracheobronchomalacia, and perform a BAL. Learner competency was assessed using a modified version of the Bronchoscopy Skills and Tasks Assessment Tool (BSTAT) (4). Expert instructors assessed 15 procedural skills and assigned a score of 1 for every competency skill appropriately performed. Each learner was assigned a competency score. A single expert instructor at each institution observed each participant individually. Deidentified data from assessment surveys were collected using Qualtrics software and were made accessible to learners on their mobile devices immediately after the course. The study was determined to be exempt from ongoing institutional review board review.

Data Analysis

Data from the model assessment instrument and curriculum assessment instrument are presented as means of individual groups with standard deviations. Data from the BSTAT instrument are presented as a tally of learners demonstrating competence.

RESULTS

Nine expert bronchoscopists from different pediatric subspecialties assessed the 3D-AM (Table 1). Responses were favorable across all domains. All operators agreed that the model had “a great deal of value” and “great relevance” and that

Table 1. Expert bronchoscopist assessments of three-dimensional airway model ($n = 9$)

Model Assessment Domain	Mean Likert Score (SD)
Physical attributes	4.2 (0.4)
Realism of experience	4.4 (0.5)
Ability to perform tasks	4.8 (0.4)
Value	5.0 (0)
Relevance	5.0 (0)
Global	4.4 (0.5)

Definition of abbreviation: SD = standard deviation.

it could be used but could also be improved.

Fourteen fellows from three different institutions and three different pediatric subspecialties participated in the curriculum in the first 2 months of fellowship training. This included two PP fellows, four PCCM fellows, and four PS fellows from hospital A, two PP fellows from hospital B, and two PP fellows from hospital C.

Learners had a favorable impression of the 3D-AM across all six domains (Table 2). All learners assigned a score of 4 or 5 to the physical attributes and realism of experience domains, suggesting that the 3D-AM was highly realistic or adequate but could be improved. Eleven found it “somewhat easy” and three found it “very easy” to perform tasks. Ten found the 3D-AM model to have “a great deal of value,” whereas four found it to have “some value.” Similarly, 11 found that the 3D-AM had “a great deal of relevance,” whereas 3 found it to have “some relevance.” When assessing the model overall, 10 suggested that the 3D-AM “can be used as is,” whereas 3 suggested that there could be improvements, and 1 fellow reported that the 3D-AM “requires improvement.” No specific comments were provided to explain this rating. The ratings across all domains (physical attributes, realism of experience, ability to perform tasks, value, relevance, and global) were similar among all incoming fellows across the three different institutions.

Learners from all institutions and across different procedural subspecialties valued the curricular experience (Table 3). All learners either agreed or strongly agreed that the course was a good use of their time, helped the learner gain technical skills, helped the learner learn airway anatomy, could be used for extra training during fellowship, and should be used for future incoming fellows. All learners except two fellows at the same institution agreed or strongly agreed that they felt more comfortable performing a bronchoscopy.

Expert instructors evaluated the procedural competency of learners using the BSTAT instrument (Table 4). All learners correctly identified the right mainstem bronchus, right upper lobe bronchus, bronchus intermedius, and mainstem bronchus. Only one learner failed to identify the right lower lobe bronchus, lingula bronchus, and left lower lobe bronchus. Two learners failed to identify the left upper lobe bronchus, and three failed to identify the right middle lobe bronchus. There was not a single learner who failed in every competency. All learners were able to successfully navigate the bronchoscope to identify specific simulated pathologies (airway compression placed at different locations per the instructor’s discretion) and perform a BAL. All learners demonstrated good technical skills of posture, hand positioning, and equipment safety, except for one fellow who did not demonstrate competence with posture, hand positioning, and keeping the scope midline and two additional fellows who were unable to keep the scope midline. Only 9 out of 14 (64.3%) adequately avoided wall trauma, as perceived by the expert instructors. Mean learner competency scores were similar across institutions among PP fellows (11.5/15, 12.5/15, and 13.5/15) but were slightly higher among fellows in PCCM (14.25/15) and PS (15/15).

When asked for qualitative impressions, learners reported that the course was “very helpful” and an “excellent learning session,” and that the model was “easy to use and very realistic.”

Table 2. Learner assessments of the three-dimensional airway model ($n = 14$)

Model Assessment Domain	Mean Likert Score (SD)
Physical attributes	
Hospital A PP fellows	5.0 (0)
Hospital A PS fellows	5.0 (0)
Hospital A PCCM fellows	4.8 (0.5)
Hospital B PP fellows	4.0 (0)
Hospital C PP fellows	4.0 (0)
Realism of experience	
Hospital A PP fellows	4.8 (0.5)
Hospital A PS fellows	5.0 (0)
Hospital A PCCM fellows	4.8 (0.5)
Hospital B PP fellows	4.0 (0)
Hospital C PP fellows	4.0 (0)
Ability to perform tasks	
Hospital A PP fellows	4.3 (0.5)
Hospital A PS fellows	4.5 (0.7)
Hospital A PCCM fellows	4.0 (0)
Hospital B PP fellows	4.0 (0)
Hospital C PP fellows	4.5 (0.7)
Value	
Hospital A PP fellows	5.0 (0)
Hospital A PS fellows	5.0 (0)
Hospital A PCCM fellows	4.5 (0.6)
Hospital B PP fellows	4.0 (0)
Hospital C PP fellows	5.0 (0)
Relevance	
Hospital A PP fellows	4.8 (0.5)
Hospital A PS fellows	5.0 (0)
Hospital A PCCM fellows	5.0 (0)
Hospital B PP fellows	4.5 (0.7)
Hospital C PP fellows	4.5 (0.7)

Table 2. *Continued.*

Model Assessment Domain	Mean Likert Score (SD)
Global	
Hospital A PP fellows	5.0 (0)
Hospital A PS fellows	5.0 (0)
Hospital A PCCM fellows	4.8 (0.5)
Hospital B PP fellows	3.0 (1.4)
Hospital C PP fellows	4.5 (0.7)

Definition of abbreviations: PCCM = pediatric critical care medicine; PP = pediatric pulmonology; PS = pediatric surgery; SD = standard deviation.

DISCUSSION

In this study, a clinical and design team developed, manufactured, and tested a 3D-printed pediatric airway for use in an educational curriculum for PFB across different institutions and subspeciality trainees. The 3D-AM was graded favorably across all domains. Learner assessments were similar among fellows across different procedural subspecialties and different institutions. Basic procedural competencies, such as anatomic landmark and pathology identification, were more easily achieved than technical skills; however, this may present a role for repeated exposures to the simulator.

Although several studies have evaluated the utility of 3D-printed airways for adult flexible bronchoscopy training among expert bronchoscopists (6, 7, 10, 12, 16) or learners with similar educational pathways (11, 13, 17), this is the first study to examine the experiences of a variety of learners in different procedural subspecialties and at different institutions using the same pediatric 3D-printed airway. The similar educational outcomes among learners suggest that the 3D-AM is potentially transferrable to different academic institutions. When combined with the low production costs, the 3D-AM has features that make it a useful tool across institutions, particularly those with limited teaching resources. Some training resources, including the size of the bronchoscope and the expert instruction, varied across centers. Nonetheless, despite these variations, the learner assessments of the 3D-AM were similar.

Some learners provided ratings that suggested that the 3D-AM could be improved, although this is an expected response to a novel simulation tool in the early stages of development (6). Although not part of the primary outcome analysis of the 3D-AM, a second-year fellow was asked to assess the airway and found that the 3D-AM does not add value after a certain competency threshold has been reached. Indeed, Ghazy and colleagues similarly identified a smaller reduction in time to bronchoscopy task completion among senior learners training with a 3D-printed airway (13). Two learners from a single institution reported that they did not "feel comfortable" performing PFB, an appropriate response among novice learners. Therefore, the 3D-AM and the PFB curriculum appeared to be an appropriate introductory course for learners with very little to no experience in PFB. This particular model might not

Table 3. Learner assessment of the entire curriculum ($n = 14$)

Curriculum Assessment	Mean Likert Score (SD)
It was a good use of my time	
Hospital A PP fellows	5.0 (0)
Hospital A PS fellows	5.0 (0)
Hospital A PCCM fellows	4.8 (0.5)
Hospital B PP fellows	4.5 (0.7)
Hospital C PP fellows	5.0 (0)
I feel comfortable performing bronchoscopy	
Hospital A PP fellows	4.8 (0.5)
Hospital A PS fellows	5.0 (0)
Hospital A PCCM fellows	4.8 (0.5)
Hospital B PP fellows	4.0 (0)
Hospital C PP fellows	3.0 (0)
It helped me gain technical skills	
Hospital A PP fellows	5.0 (0)
Hospital A PS fellows	5.0 (0)
Hospital A PCCM fellows	5.0 (0)
Hospital B PP fellows	4.0 (0)
Hospital C PP fellows	4.5 (0.7)
It helped me learn airway anatomy	
Hospital A PP fellows	5.0 (0)
Hospital A PS fellows	5.0 (0)
Hospital A PCCM fellows	5.0 (0)
Hospital B PP fellows	4.0 (0)
Hospital C PP fellows	4.0 (0)
It will be useful for extra training during my fellowship	
Hospital A PP fellows	5.0 (0)
Hospital A PS fellows	5.0 (0)
Hospital A PCCM fellows	5.0 (0)
Hospital B PP fellows	4.0 (0)
Hospital C PP fellows	5.0 (0)

Table 3. *Continued.*

Curriculum Assessment	Mean Likert Score (SD)
It should be used for future incoming fellows	
Hospital A PP fellows	5.0 (0)
Hospital A PS fellows	5.0 (0)
Hospital A PCCM fellows	5.0 (0)
Hospital B PP fellows	4.0 (0)
Hospital C PP fellows	5.0 (0)

For definition of abbreviations, *see* Table 2.

be suitable for more experienced bronchoscopists. More advanced skills, such as teaching bronchoscopy and managing complications, were not assessed in this study. The benefit of 3D printing is the ability to create rare and complex pathologies that might be better suitable for more experienced bronchoscopists.

Perceived learner competencies, as measured by the mean learner competency scores assigned from the BSTAT instrument, were slightly lower

Table 4. Bronchoscopy Skills and Tasks Assessment Tool ($n = 14$)

Skills and Tasks	Number of Learners Achieving Competence
Identification of right mainstem bronchus	14
Identification of right upper lobe bronchus	14
Identification of bronchus intermedius	14
Identification of right middle lobe bronchus	11
Identification of right lower lobe bronchus	13
Identification of left mainstem bronchus	14
Identification of left upper lobe bronchus	12
Identification of lingula bronchus	13
Identification of left lower lobe bronchus	14
Technical skills—posture	13
Technical skills—hand position	13
Technical skills—equipment safety	14
Scope centered and kept in midline	11
Pathology identified/bronchoalveolar lavage done well	14
Airway wall trauma avoided	9

among PP fellows compared with the more procedure-based fellows in PCCM and PS. The greater procedural competency among pediatric surgery and critical care fellows possibly reflects more extensive procedural and simulation experience among those learners, but a larger study is needed to determine whether the model has equal educational impact among medical and surgical subspecialty fellows.

Overall, learners demonstrated competency identifying airway anatomy and tracheobronchomalacia. Competency scores of technical skills, such as keeping the bronchoscope centered in midline and avoiding airway wall trauma, were generally lower. In a study evaluating the utility of a 3D-printed airway compared with commercially available bronchial simulators, participants considered the 3D-printed airway to be more realistic, particularly with anatomy identification, but rated the 3D-printed airway less favorably for intervention simulation (7). Realism, therefore, and the ability to engineer the model for unique lifelike simulation with computer-aided design, coloring, and textures, appear to lend favorably to 3D printing compared with virtual reality and prefabricated models. Technical aspects of bronchoscopy have previously been shown to improve with practice. Among a group of learners using a 3D-printed airway designed for adult bronchoscopy training, the time to task completion and quality of skills improved with repeated attempts (14). The 3D-AM was robust enough for repeated practice with novice learners.

Limitations

There are several limitations to our study. The small number of incoming pediatric fellows at the three teaching institutions limited our ability to make strong statistical comparisons. However, the learner assessments provided substantial qualitative data on the utility, feasibility, and transferability of the 3D-AM and curriculum itself, which can be modified and improved. Although the 3D-AM demonstrated durability over time, it suffered mild quality deterioration with repeated disassembly and reassembly required for shipment between institutions.

Conclusions

A 3D-AM is a promising tool for teaching PFB skills to learners in different subspecialties at different teaching institutions with little to no experience with PFB at minimal cost. A 3D-printed airway model, therefore, may be an appropriate and feasible modality for improving and standardizing PFB training across different teaching institutions in the country and abroad and reducing educational disparities.

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