Development of a 3D Printed Lung Model Made of Synthetic Materials for Simulation

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Abstract

Background Considering the complexity of lung structures and the difficulty of thoracoscopic surgery, simulation-based training is of paramount importance for junior surgeons. Here, we aim to design a high-fidelity lung model through utilizing the three-dimensional (3D) printing technology combined with synthetic materials to mimic the real human lung.

Methods The 3D printed lung model was manufactured based on the computed tomography images of a randomly selected male patient. Synthetic materials were used for the construction of lung parenchyma, blood vessels, and bronchi. Then, the model was assessed in terms of its visual, tactile, and operational features by participants (the senior surgeons, junior surgeons, and medical students), who were asked to complete the specially designed survey-questionnaires.

Results A 3D printed model of the right lung made of synthetic materials was successfully fabricated. Thirty subjects participated in our study (10 senior surgeons, 10 junior surgeons, and 10 medical students). The average visual evaluation scores for senior surgeons, junior surgeons, and medical students were 3.97 ± 0.61, 4.56 ± 0.58, 4.76 ± 0.49, respectively. The average tactile evaluation scores were 3.40 ± 0.50, 4.13 ± 0.68, 4.00 ± 0.64, respectively. The average operation evaluation scores were 3.33 ± 0.83, 3.93 ± 0.66, 4.03 ± 0.66, respectively. Significant lower scores were obtained in the group of the senior surgeons compared with the other two groups.

Conclusion A high level of fidelity was exhibited in our 3D printed lung model and it could be applied as a promising simulator for the surgical training in the future.

Keywords
- ► 3D printed lung model
- ► synthetic materials
- ► fidelity
- ► surgical training
- ► thoracoscopic surgery

Introduction

Lung cancer has a greater mortality rate than that of other malignant tumors and the incidence of lung cancer will undoubtedly increase as the consequence of an aging population.[1,2] In a great deal of treatments to improve the prognosis of patients with lung cancer, surgery still occupies the space of top prominence, especially for those with early stage disease. Recently, there is a growing tendency for patients to choose thoracoscopic surgery rather than conventional thoracotomy, mainly because it has advantages of less cost, reduced trauma, and shorter hospital stay.[3–5] However, thoracoscopic surgery requires mastery of a specialized skill set, such as unique endoscopic view and specially designed endoscopic instruments, making it difficult for young surgeons to adapt and learn. An estimated of 50

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cases must be performed before a novice can perform thoracoscopic lobectomy independently.[6]

Simulator-based learning is an effective way to improve the capability of young surgeons as well as to reduce their learning curves of thoracoscopic surgery.[7,8] In this way, they can avoid making mistakes as the result of the unfamiliarity of anatomical structures and reduce perioperative mortality and morbidity rates. Previously, a large number of training simulators have been reported, such as animal models and three-dimensional (3D) printed models.[9–11] Animal models allow surgical training in a condition similar to the live human organ but have some disadvantages in terms of considerable expense, ethical issues, and anatomic differences.[12,13] 3D printed models are comparatively new simulators and become a major area of focus, with applications lying in not only surgical training but many other medical fields.[14–16] However, most existing 3D printed models focus on anatomical accuracy while lack precise mimicry of the physical properties of real tissues.

As described by Tong et al, the utility of a good simulator depends on its fidelity and validity.[13] Fidelity is a fundamental parameter when assessing the practicability of a simulator, while validity refers to the operational experience on mechanical properties. In the study of Qiu et al, they designed a high-fidelity patient-specific 3D printed prostate model with physical properties of customized materials as well as integrated soft electronic sensors, which has a wide range of advantages in simulated training.[17] Although many lung models have been applied to simulate thoracoscopic surgery over the past decade,[13,18,19] none of them utilized synthetic materials that feel realistic. Therefore, we aim to design a high-fidelity model by using 3D printing technology combined with synthetic materials to mimic the appearance, structure, and other aspects of the live lung tissue, which could be valuable for the education of junior surgeons.

Materials and Methods

Image Processing and 3D Printing

In the present study, the digital imaging and communications in medicine data of thin-slice (1 mm) computed tomographic images of a randomly selected male was chosen as a reference model. The 3D reconstruction of blood vessels and bronchi was performed using software Mimics 21.0 (Materialise NV, 15 Technologielaan, 3001 Leuven, Belgium). A SPS350C (Hengtong Intelligent Machine Co., Ltd., China) 3D printer was used to produce the right lung model with stereolithography technology. The materials used for manufacturing model are summarized in ►**Table 1**.

Table 1 Materials used for manufacturing 3D printed lung model

Structures	Materials
Lung parenchyma	Cellulose, glycerin, ethylene glycol, silica, ferric chloride, polyvinyl chloride, polyol-based polymers, polyvinyl alcohol, triethanolamine oleate, sodium dodecyl sulfate
Blood vessels	Cellulose, glycerin, ferric chloride, polyvinyl alcohol, polyol-based polymers, potassium hydroxide
Bronchi	Cellulose, glycerin, ferric chloride, polyvinyl alcohol, polyol-based polymers, potassium hydroxide, polyvinyl chloride

Abbreviation: 3D, three-dimensional.

Evaluation of the 3D Models

Following the viewing and feeling touch tests, the study participants evaluated the 3D lung model of its fidelity and validity using specially designed survey-questionnaires in terms of its visual, tactile, and operational features. Fidelity was assessed by visual appearance and tactile texture and validity was assessed by operational experience. The ratings to the questions were made on a 5-point Likert scale where 1 represents strongly unsatisfied, 2 represents unsatisfied, 3 represents neither unsatisfied nor satisfied, 4 represents satisfied, and 5 represents strongly satisfied. All individual data were kept strictly confidential. The study was approved by the ethics committee of Peking University People's Hospital (protocol no. 2018PHB219–01).

Statistical Analysis

Statistical significance between groups was determined by one-way analysis of variance. Differences were considered to be statistically significant when the p-value was less than 0.05. All data were analyzed using SPSS version 26.0 software (IBM, Armonk, New York, United States) and GraphPad Prism 8 (GraphPad Software, San Diego, California, United States).

Results

The 3D model of the right lung was successfully printed (►**Fig. 1**), which was able to closely resemble the feel of real lung, consisting of three lobes and exhibiting a pink appearance. Blood vessels and bronchi were printed in white color so they could be clearly visualized during operation. All critical structures were preserved including right pulmonary arterial and venous systems, and branches of right principal bronchus.

Thirty participants were involved in the study. Of whom, 10 were senior surgeons, 10 were junior surgeons, and 10 were medical students. The assessments of the model on the basis of visual, tactile, and operational aspects (►**Fig. 2**) were completed by all participants. Meanwhile, the discrepancy among the three groups of participants was compared. The average visual evaluation scores for senior surgeons, junior surgeons, and medical students were 3.97 ± 0.61, 4.56 ± 0.58, and 4.76 ± 0.49, respectively. The average tactile evaluation scores were 3.40 ± 0.50, 4.13 ± 0.68, and 4.00 ± 0.64, respectively. The average operational evaluation scores were 3.33 ± 0.83, 3.93 ± 0.66, and 4.03 ± 0.66, respectively. The average score of the evaluation about the model in each group was greater than 3 points (►**Fig. 3**), which indicated that our 3D printed lung model was accepted by all of the participants regardless of the surgical experience. Of note, compared with the other two groups, senior surgeons gave significantly lower scores in terms of many

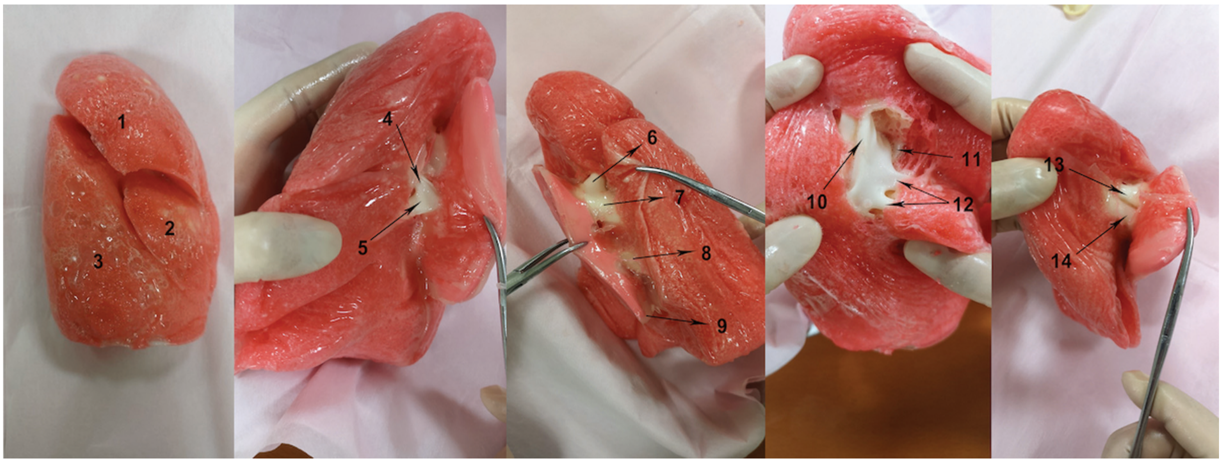

Fig. 1 The visual appearance of three-dimensional printed lung models. 1—upper lobe, 2—middle lobe, 3—lower lobe, 4—upper lobe vein, 5—middle lobe vein, 6—upper lobe bronchus, 7—intermediate bronchus, 8—inferior pulmonary vein, 9—pulmonary ligament, 10—ascending branch of the posterior pulmonary artery, 11—central veins, 12—middle lobe artery, 13—upper lobe bronchus, 14—apical–anterior arterial trunk.

Fig. 2 Simulation of thoracoscopic surgery of lung.

parameters (►**Table 2**), which indicated that further improvements in our model are needed to completely conform to the requirement of surgical training.

Discussion

In this study, we fabricated a 3D printed lung made of synthetic materials resembling real lung tissue. Our 3D printed lung model was accepted by all of the participants in visual, tactile, and operational aspects regardless of the surgical experience. We hope this novel lung model could be used to facilitate junior surgeons to improve their thoracoscopic surgical skills and increase their self-confidence in the surgery.

A wide variety of thoracoscopic simulators have been reported in the literature for surgical training. Previous simulators usually utilized porcine lungs fixed in the box for surgical training.[13,18,19] However, this was limited by the high cost and ethical concerns. The 3D virtual reality simulators can offer high fidelity and create an ideal environment that captures anatomical details with high accuracy, but they cannot provide feedback to trainees regarding their performance.[20] As we have stated previously, fidelity and validity are two significant parameters in evaluating the practicality of a mode. The novice needs to feel as if they are actually performing an operation. By offering practice in the context of lifelike situations, participants can be more skilled in the operation, can deal with complications more efficiently, and avoid unnecessary injury to patients eventually.

Our model is of high fidelity. First, the 3D printed lung model we introduced is based on 3D printing technology. The size ratio of the model to the patient's true lung is 1:1, with a good visual appearance in tridimension (length, width, and height) and a high level of anatomic accuracy of pulmonary vessels and bronchi as well as the spatial relationship between those structures. These advantages aid in the enhancement of memorization of critical lung anatomic landmarks in real space and anticipation of common variations at the time of dissection for surgeons who have less experience performing surgeries. Second, to create a realistic simulation, the model was made of proper materials that can replicate the feel of real organs. Simulation models made of synthetic materials with some physical properties replicating real tissue have been reported in many organs in the

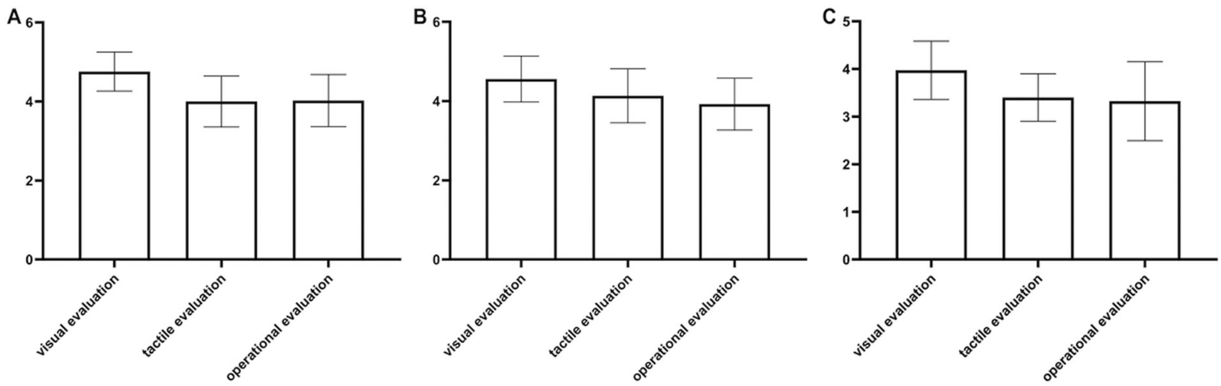

Fig. 3 The visual, tactile, and operational assessments of the three-dimensional printed model among different groups: (**A**) medical students, (**B**) junior surgeons, and (**C**) senior surgeons.

Table 2 Assessment results of participants

Parameters	Test score, mean (SD)			*p*-Value
	Medical students	Junior surgeons	Senior surgeons	
Visual evaluation				
Visual appearance	4.90 ± 0.32	4.80 ± 0.42	4.30 ± 0.48	0.007[a]
Anatomy of anterior hilar	4.90 ± 0.52	4.60 ± 0.70	3.90 ± 0.74	0.004[a]
Anatomy of upper hilar	4.90 ± 0.32	4.70 ± 0.48	4.10 ± 0.57	0.002[a]
Anatomy of posterior hilar	4.90 ± 0.32	4.90 ± 0.32	4.20 ± 0.42	<0.001[a]
Structures surrounding the oblique and horizontal fissures	4.90 ± 0.48	4.80 ± 0.42	4.00 ± 0.67	<0.001[a]
Vessel diameter and wall thickness	4.50 ± 0.53	4.30 ± 0.48	3.60 ± 0.52	0.001[a]
Vessel sheath	4.20 ± 0.79	3.80 ± 0.42	3.70 ± 0.67	0.207
Tactile evaluation				
Lung parenchyma texture	3.90 ± 0.57	4.20 ± 0.63	3.20 ± 0.42	0.001[a]
Vessels texture	4.10 ± 0.57	4.20 ± 0.63	3.70 ± 0.48	0.131
Bronchi texture	4.00 ± 0.82	4.00 ± 0.82	3.30 ± 0.48	0.060
Operational evaluation				
Lung deformation	4.00 ± 0.47	3.80 ± 0.79	2.90 ± 0.88	0.005[a]
Vessel elasticity	4.10 ± 0.88	4.00 ± 0.67	3.60 ± 0.84	0.350
Vessel sheath toughness	3.90 ± 0.74	4.00 ± 0.47	3.30 ± 0.82	0.068
Tissue conductivity	4.10 ± 0.57	3.90 ± 0.74	3.50 ± 0.71	0.148

Abbreviation: SD, standard deviation.
[a] $p < 0.05$ was considered significant.

previous literature, such as renal tissues and prostate tissues, and popular materials being used were plastic/resin, silicone, acrylic, and a variety of polymers.[17,21,22] The lung model that we developed was primarily made of polymer-based materials with some considerable resemblances compared with real lung tissue in terms of the shape, color, and texture.

As for validity, we have done some preliminary tests in a simulated thoracoscopic environment, such as lung compliance, vascular elasticity, sheath toughness, tissue conductivity, and most indicators were considered acceptable. However, further improvements in our model are needed with absolute certainty. For instance, the lung parenchyma was not easy to deform and we are trying to ameliorate this deficiency by adjusting the component ratios of the basic materials or seeking other more deformable materials. Besides that, more evidence is required to assess the effectiveness of this novel model.

Conclusion

In conclusion, a 3D printed lung made of synthetic materials was fabricated in our study, which exhibited a high level of fidelity and might serve as a promising simulator for thoracoscopic surgical training in the future.

Data Availability Statement
Any further inquiries can be directed to the corresponding author.

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Conflict of Interest
The authors declared that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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