

Development and Validation of a Low-Cost Three-Dimensional-Printed Simulator for Bronchial and Pulmonary Vascular Reconstruction Training.

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Abstract

Background

Three-dimensional (3D) printing has expanded the possibilities for developing patient-specific anatomical models and simulation platforms for medical education. However, validated, affordable simulators for complex thoracic reconstructive procedures remain limited. This study aimed to develop and validate a reusable, low-cost 3D-printed simulator for bronchial and pulmonary vascular reconstruction.

Methods

A prospective multicenter validation study was performed involving 36 participants with different levels of surgical experience (13 medical students, 10 surgical residents, and 13 senior thoracic surgeons). Anatomical molds were designed using computer-aided design software and fabricated using fused deposition modeling technology. Silicone bronchial and pulmonary vascular models were produced from the printed molds and incorporated into a thoracic access platform. Face, content, and construct validity were assessed using standardized questionnaires and objective performance measures.

Results

The simulator demonstrated good internal consistency for face-validity assessment (Cronbach's $\alpha = 0.851$) and excellent internal consistency for content validity (Cronbach's $\alpha = 0.947$). Construct validity was supported by significant differences in performance across participant experience levels during restricted reconstruction tasks. Repeated simulator use significantly reduced procedural completion time ($P < 0.001$).

Conclusions

This study demonstrates that low-cost 3D printing can be used to manufacture reproducible and educationally valid simulators for complex thoracic reconstruction. The proposed platform provides an accessible solution for simulation-based surgical training and may facilitate wider implementation of competency-based education in thoracic surgery.

Highlights

- A low-cost 3D-printed simulator was developed for complex thoracic reconstruction.
- The simulator demonstrated face, content, and construct validity.

- Performance improved significantly after repeated simulation-based practice.
- The model distinguished technical performance across experience levels.
- The platform offers an affordable tool for competency-based thoracic surgery training.

INTRODUCTION

Three-dimensional (3D) printing has emerged as one of the most transformative technologies in modern medicine, enabling the rapid production of patient-specific anatomical models, customized surgical instruments, implants, and educational simulators. Its capacity to convert digital imaging data into tangible physical models has substantially expanded applications in surgical planning, medical education, procedural rehearsal, and device development. As manufacturing costs continue to decrease and accessibility improves, 3D printing is increasingly incorporated into clinical and educational workflows across multiple medical specialties [1–3].

Among its educational applications, 3D printing has demonstrated particular value in simulation-based training. Anatomically accurate models can reproduce procedural steps that are difficult to practice using conventional educational resources while offering reproducibility, customization, and lower costs than cadaveric or animal models. Recent systematic reviews have highlighted the growing role of 3D-printed simulators in surgical education but have also emphasized the need for stronger evidence supporting their educational validity and clinical relevance [4–6, 19].

Recent advances in additive manufacturing have facilitated the development of reusable silicone models produced from 3D-printed molds, allowing realistic simulation of tissue handling while maintaining low manufacturing costs. Such platforms offer the possibility of combining anatomical fidelity with scalability and reproducibility, making them attractive for competency-based surgical education [9–12].

The present study describes the development, manufacturing process, and educational validation of a reusable low-cost 3D-printed simulator for bronchial and pulmonary vascular reconstruction. We evaluated evidence of face, content, and construct validity across participants with different levels of surgical expertise and assessed the effect of repeated simulator use on procedural performance. By integrating affordable additive manufacturing with structured educational evaluation, this work aims to provide a reproducible simulation platform suitable for advanced thoracic surgery training.

MATERIALS AND METHODS

Study Design and Ethical Approval

A cross-sectional observational validation study was conducted to develop and evaluate a low-cost three-dimensional (3D)-printed surgical simulator designed for bronchial and pulmonary vascular anastomosis training.

The study protocol was approved by the Navarra Clinical Research Ethics Committee (PI_2022/21; April 8, 2022). Written informed consent was obtained before participation.

Development and Manufacturing of the Surgical Simulator

The simulator was designed to reproduce key technical aspects of complex thoracic surgical procedures requiring bronchial and vascular reconstruction.

Two anatomical models were developed: a bronchial model and a pulmonary vascular model. Digital designs were generated using computer-aided design (CAD) software based on standard anatomical references. Three-dimensional molds were subsequently manufactured using fused deposition modeling (FDM) technology with polylactic acid (PLA). The final anatomical structures were produced by casting platinum-cured silicone (Dragon Skin™, Smooth-On Inc., Macungie, PA, USA) into the printed molds. This material was selected due to its flexibility, durability, and ability to reproduce relevant tactile characteristics during surgical manipulation and suturing.

The vascular model reproduced the dimensions of the pulmonary artery, allowing vascular anastomosis training (Fig. 1). The bronchial model was designed to reproduce the anatomical characteristics of the airway, including cartilaginous rings and a membranous posterior wall, allowing performance of interrupted and continuous bronchial suturing techniques (Fig. 2). To reproduce the technical limitations of open thoracic surgery, a restricted-access thoracic platform was developed using 3D printing technology. This platform simulated a confined operative field, requiring appropriate instrument positioning, depth perception, and surgical exposure management (Fig. 3).

The estimated manufacturing cost was approximately €35 for the bronchial model, €40 for the vascular model, and €39 for the thoracic platform.

Participants and Validation Process

Following current recommendations for validation in medical education, we collected multiple sources of validity evidence, including evidence based on test content, internal structure, and relationships with other variables. Participants were prospectively stratified into three predefined groups according to surgical experience:

- - Medical students (n = 13)
- - Surgical residents (thoracic, vascular and general surgery) (n = 10)
- - Thoracic surgeons (n = 13)

Thoracic surgeons and residents were recruited from participating Spanish institutions, including Vall d'Hebron University Hospital, San Pedro Hospital (Logroño), Marqués de Valdecilla University Hospital, Donostia University Hospital, and University of Navarra Hospital. Medical students were recruited from

the University of Navarra and had previous basic training in surgical suturing techniques. All participants received standardized instructions regarding the simulator and assigned tasks. No additional practice period was provided before evaluation.

Surgical Tasks and Performance Assessment

Participants performed interrupted and continuous suturing techniques on both airway and vascular models. (Fig. 4)

Tasks were performed under two conditions:

1. Standard unrestricted bench-top conditions.
2. Restricted-access conditions using the thoracic platform.

Performance variables included:

- - Successful completion of assigned suturing tasks.
- - Type of suture performed.
- - Procedural completion time.

Each participant performed repeated attempts to evaluate changes in performance following initial exposure to the simulator. (Supplementary Video 1)

All evaluations were performed under the supervision of the same research team using standardized assessment criteria.

Simulator Validation

Face validity and content validity were assessed using structured questionnaires based on a five-point Likert scale (1 = strongly disagree; 5 = strongly agree). (Supplementary Fig. 1)

Face validity evaluated anatomical appearance, material properties and realism of surgical manipulation.

Content validity assessed

Educational usefulness, suitability for technical skill acquisition and potential application in surgical training and assessment.

Construct validity

was assessed by comparing simulator performance across three predefined levels of surgical expertise. The expert reference group consisted of senior board-certified thoracic surgeons with extensive experience in complex bronchial and pulmonary vascular reconstruction. The simulator's ability to

discriminate technical performance between novices, trainees, and expert surgeons was considered evidence supporting construct validity.

Statistical Analysis

Continuous variables are presented as mean $\pm$ standard deviation (SD), whereas categorical variables are reported as frequencies and percentages. The internal consistency of the face- and content-validity questionnaires was evaluated using Cronbach's alpha coefficient. Comparisons among the three experience groups were performed using the Kruskal–Wallis test. When statistically significant differences were identified, pairwise comparisons were performed using the Mann–Whitney U test. Associations between participant experience and successful completion of reconstructive tasks were evaluated using Pearson's chi-square test.

Differences in procedural completion time between repeated simulation attempts were analyzed using the Wilcoxon signed-rank test.

All statistical analyses were performed using IBM SPSS Statistics version 25.0 (IBM Corp., Armonk, NY, USA). Statistical significance was defined as a two-sided P value < 0.05.

RESULTS

Participant Characteristics

Thirty-six participants completed the validation study and were stratified according to surgical experience into three predefined groups: medical students (n = 13), surgical residents (n = 10), and senior board-certified thoracic surgeons (n = 13).

Thoracic surgeons and residents were recruited from five tertiary referral hospitals in Spain, whereas medical students were recruited from the University of Navarra after standardized instruction in basic surgical suturing.

All participants completed the assigned simulation tasks and the validation questionnaires. No simulator failures, material deterioration, or adverse events occurred during the study.

Simulator Characteristics

The developed platform consisted of three reusable components: a bronchial reconstruction model, a pulmonary vascular reconstruction model and a thoracic access platform reproducing restricted operative exposure.

The manufacturing process allowed reproducible fabrication using 3D-printed molds and platinum-cured silicone, with an estimated total production cost of approximately €114 per complete simulator.

Construct Validity

Construct validity was assessed by comparing simulator performance across participants with different levels of surgical expertise. All participants successfully completed unrestricted interrupted and continuous bronchial and vascular sutures. However, significant differences emerged when procedures were performed under restricted-access conditions using the thoracic platform. Senior thoracic surgeons achieved significantly higher completion rates than residents and medical students during technically demanding tasks involving limited operative exposure.

For interrupted vascular sutures performed within the thoracic platform, successful completion increased from 53.8% among students to 90.0% among residents and 92.3% among senior thoracic surgeons ($P = 0.034$). Similarly, continuous vascular suturing under restricted conditions demonstrated marked differences across experience levels (7.7%, 70.0%, and 92.3%, respectively; $P < 0.001$). Comparable findings were observed for bronchial reconstruction. Successful completion of interrupted bronchial sutures within the thoracic platform increased progressively according to surgical experience (30.8%, 70.0%, and 100%, respectively; $P = 0.001$), whereas continuous bronchial sutures demonstrated the greatest discrimination between groups (7.7%, 80.0%, and 92.3%; $P < 0.001$).

These findings demonstrate the ability of the simulator to discriminate technical performance according to surgical expertise, supporting evidence of construct validity. (Table 1)

Table 1

Distribution of the performance of suturing techniques according to level of training and association results

Evaluated technique	Type of Model	Students (n = 13) n (%)	Residents (n = 10) n (%)	Surgeons (n = 13) n (%)	χ^2 (gl)	p
Interrupted suture	Arterial	13 (100)	10 (100)	13 (100)	-	-
Interrupted suture	Vascular model with thoracic platform	7 (53.8)	9 (90.0)	12 (92.3)	6.76 (2)	0.034
continuous suture	Arterial	12 (92.3)	10 (100)	12 (92.3)	0.81 (2)	0.665
continuous suture	Vascular model with thoracic platform	1 (7.7)	7 (70.0)	12 (92.3)	20.02 (2)	< 0.001
Interrupted suture	Airway	13 (100)	10 (100)	13 (100)	-	-
Interrupted suture	Airway model with thoracic platform	4 (30.8)	7 (70.0)	13 (100)	14.09 (2)	0.001
continuous suture	Airway	13 (100)	10 (100)	13 (100)	-	-
continuous suture	Airway model with thoracic platform	1 (7.7)	8 (80.0)	12 (92.3)	21.82 (2)	< 0.001

Procedural Performance and Learning Effect

Repeated simulator use resulted in improved procedural efficiency. Mean procedural completion time decreased significantly from 962.46 ± 530.39 seconds during the first attempt to 858.37 ± 430.36 seconds during the second attempt ($P < 0.001$). The largest improvements were observed among less experienced participants, whereas senior thoracic surgeons demonstrated smaller reductions in procedural time, consistent with their higher baseline performance. Time reductions varied according to reconstruction type and suture technique (Table 2), with the greatest improvements observed during continuous bronchial reconstruction.

These findings suggest early acquisition of technical skills through deliberate simulator-based practice.

Table 2
Time difference (Time 2 - Time 1) according to suture type

Suture type	N	Mean $\pm$ SD	95% IC	H	p
Continuous suture in airway model	35	-201.60 $\pm$ 338.32	-317.82, -85.38	6.330	0.097
Continuous suture in artery model	31	-85.55 $\pm$ 217.96	-165.50, -5.60		
Continuous suture in Airway model with thoracic platform	19	2.37 $\pm$ 187.09	-87.81, 92.54		
Continuous suture in Vascular model with thoracic platform	18	-58.78 $\pm$ 102.62	-109.81, -7.75		

Face Validity

Participants from all three experience groups rated the simulator favorably regarding anatomical appearance, tissue characteristics, and technical realism (Table 3).

The face-validity questionnaire demonstrated good internal consistency (Cronbach's $\alpha = 0.851$). Overall ratings remained consistently high across participant groups. Senior thoracic surgeons tended to provide slightly more critical evaluations of anatomical fidelity and tissue realism than less experienced participants did, although the simulator was considered an appropriate representation of bronchial and pulmonary vascular reconstruction by all groups.

Table 3
Face validity assessment by groups

Item	Students (N = 13)	Residents (N = 10)	Surgeons (N = 13)
	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD
Tissue anatomy as expected	4.23 $\pm$ 0.60	4.20 $\pm$ 0.42	3.85 $\pm$ 0.80
Levels of tension similar to reality	4.70 $\pm$ 0.48	4.10 $\pm$ 0.74	3.85 $\pm$ 1.07
Airway model close to reality	4.70 $\pm$ 0.48	4.30 $\pm$ 0.48	3.77 $\pm$ 1.01
Improvement in airway suturing technique	4.75 $\pm$ 0.45	4.20 $\pm$ 0.79	4.31 $\pm$ 0.63
Airway simulator suitable for teaching	4.92 $\pm$ 0.29	4.70 $\pm$ 0.48	4.54 $\pm$ 0.78
Torso model increases complexity	4.63 $\pm$ 0.74	4.80 $\pm$ 0.42	4.46 $\pm$ 0.78
Artery model close to reality	4.40 $\pm$ 0.70	4.20 $\pm$ 0.79	4.00 $\pm$ 0.82
Improvement in artery suturing technique	4.33 $\pm$ 0.78	4.40 $\pm$ 0.97	4.38 $\pm$ 0.87
Artery simulator suitable for teaching	4.92 $\pm$ 0.29	4.50 $\pm$ 0.53	4.23 $\pm$ 1.17

Content Validity

Participants reported high educational value for both bronchial and pulmonary vascular models (Table 4). The content-validity questionnaire demonstrated excellent internal consistency, Cronbach's $\alpha = 0.947$.

The simulator was consistently rated as useful for:

- acquisition of reconstructive technical skills;
- competency-based training;
- trainee assessment;
- repeated deliberate practice.

Although senior thoracic surgeons reported lower scores for the necessity of simulation compared with students and residents, overall educational usefulness remained favorable across all participant groups.

Table 4
Evaluation of the items in the content area according to the level of training

Item	Students (N = 13) Mean $\pm$ SD	Residents (N = 10) Mean $\pm$ SD	Surgeons (N = 13) Mean $\pm$ SD
Using the simulator gives confidence in reproducing the technique	4.75 $\pm$ 0.46	4.40 $\pm$ 0.97	4.08 $\pm$ 0.95
Using the simulator helps the learning process	5.00 $\pm$ 0.00	4.80 $\pm$ 0.42	4.69 $\pm$ 0.75
The use of the torso model helps in the adaptation of the complex suture	4.82 $\pm$ 0.41	4.60 $\pm$ 0.52	4.00 $\pm$ 1.00
The airway simulator is useful in learning	4.92 $\pm$ 0.28	4.60 $\pm$ 0.52	4.31 $\pm$ 1.03
The artery simulator is useful for learning.	5.00 $\pm$ 0.00	4.60 $\pm$ 0.52	4.46 $\pm$ 0.78
The airway simulator is necessary for learning.	4.15 $\pm$ 0.38	4.40 $\pm$ 0.52	3.00 $\pm$ 1.08
The artery simulator is necessary for learning.	4.08 $\pm$ 0.28	4.40 $\pm$ 0.52	3.08 $\pm$ 1.12
The airway simulator is useful for monitoring learning	4.69 $\pm$ 0.48	4.56 $\pm$ 0.53	4.23 $\pm$ 1.17
The artery simulator is useful for monitoring learning.	4.77 $\pm$ 0.44	4.40 $\pm$ 0.52	4.31 $\pm$ 0.86
The airway simulator is necessary for monitoring learning.	4.15 $\pm$ 0.69	4.30 $\pm$ 0.68	3.08 $\pm$ 0.76
The artery simulator is necessary for monitoring learning.	4.08 $\pm$ 0.64	4.30 $\pm$ 0.68	3.15 $\pm$ 0.80
The airway simulator is useful for evaluating learning.	4.69 $\pm$ 0.48	4.60 $\pm$ 0.52	4.46 $\pm$ 0.97
The artery simulator is useful for evaluating learning	4.77 $\pm$ 0.44	4.40 $\pm$ 0.70	4.38 $\pm$ 1.04
The airway simulator is necessary for evaluating learning.	4.00 $\pm$ 0.58	4.20 $\pm$ 0.79	3.00 $\pm$ 0.71
The artery simulator is necessary to assess learning.	4.00 $\pm$ 0.58	4.40 $\pm$ 0.70	3.00 $\pm$ 0.82

DISCUSSION

Three-dimensional (3D) printing has become an increasingly important technology in modern medicine because enables the rapid fabrication of patient-specific anatomical models, customized devices, and simulation platforms using reproducible digital workflows. In recent years, its role has expanded from

surgical planning to procedural simulation and medical education, providing affordable alternatives to traditional training models while facilitating widespread dissemination of standardized educational resources [7–9, 15].

In the present multicenter study, we developed and validated a reusable low-cost simulator for bronchial and pulmonary vascular reconstruction manufactured using 3D-printed molds and platinum-cured silicone. Our principal findings demonstrate that additive manufacturing can successfully generate anatomically reproducible simulation models capable of supporting complex technical skills training. Beyond anatomical replication, the simulator demonstrated evidence supporting face, content, and construct validity while significantly improving procedural efficiency following repeated practice.

Recent systematic reviews have highlighted the growing use of additive manufacturing for surgical education, emphasizing its ability to produce customizable anatomical models with relatively low production costs. However, they also conclude that robust educational validation remains limited and that many published studies focus primarily on anatomical realism rather than objective educational performance [8, 11, 16]. Our study addresses this limitation by combining a reproducible manufacturing process with a structured validation methodology across three different levels of surgical expertise.

Unlike many previously described thoracic models, which have primarily focused on preoperative planning or thoracoscopic anatomical orientation [9, 12, 15], the present simulator was specifically designed to reproduce technically demanding bronchial and pulmonary vascular reconstruction. The hybrid manufacturing strategy employed in this study combines the geometric accuracy of fused deposition modeling with the mechanical properties of platinum-cured silicone, allowing repeated needle passage while maintaining dimensional reproducibility and low manufacturing costs. This approach offers practical advantages over directly printed flexible models by simplifying replacement of damaged components without reproducing the entire simulator.

One of the major advantages of additive manufacturing is the possibility of rapid design iteration. Once the digital model has been generated, modifications in anatomical dimensions, procedural complexity, or educational objectives can be implemented without substantial increases in production costs. Such flexibility facilitates continuous refinement of simulation platforms and supports adaptation to different surgical procedures or training levels. Similar advantages have been described in recent reviews addressing additive manufacturing for medical education and surgical simulation [8, 15].

The educational performance of the simulator also deserves attention. Construct validity was supported by significant differences in technical performance between medical students, surgical residents, and senior thoracic surgeons, indicating that the platform discriminates procedural skills according to surgical experience. Furthermore, repeated simulator use significantly reduced procedural completion time, supporting previous evidence demonstrating that simulation-based deliberate practice contributes to progressive acquisition of technical skills [2–4, 10, 18, 19]. Although procedural efficiency should not be interpreted as a surrogate for operative competence, these findings suggest that additive

manufacturing can provide not only anatomically accurate models but also educationally effective training platforms.

Affordability remains another important advantage of the proposed manufacturing strategy. High-fidelity commercial simulators frequently require expensive proprietary materials and specialized infrastructure, limiting their implementation in many training centers. In contrast, our simulator can be manufactured using commercially available fused deposition modeling technology and silicone casting techniques at a total production cost of approximately €114. This relatively low cost facilitates repeated use, replacement of individual components, and local production, characteristics that are increasingly recognized as major advantages of additive manufacturing in healthcare [8, 15–17].

The multicenter validation further strengthens the present study. Evaluation by senior thoracic surgeons from several tertiary referral hospitals ensured that anatomical realism and procedural relevance reflected expert clinical opinion rather than trainee perception alone. Inclusion of participants with three distinct levels of surgical expertise also provided robust evidence supporting construct validity, which remains one of the most important indicators of educational performance for simulation devices [2, 3, 11].

Several limitations should be acknowledged. First, although silicone reproduces many tactile characteristics relevant for bronchial and pulmonary vascular suturing, it cannot replicate biological tissue behavior, including bleeding, tissue perfusion, inflammation, or healing. Second, only one manufacturing strategy combining fused deposition modeling and platinum-cured silicone was evaluated; future studies should investigate alternative additive manufacturing technologies and emerging printable elastomeric materials. Finally, the present investigation evaluated educational validity within a simulated environment but did not assess transfer validity or long-term skill retention, both of which represent important areas for future research.

Future developments should explore patient-specific simulation using computed tomography-derived anatomical models, incorporation of multi-material printing technologies to improve tissue fidelity, and integration of artificial intelligence for automated technical performance assessment. These advances may further expand the role of additive manufacturing from anatomical replication toward personalized, competency-based surgical training platforms [9, 13, 15, 16].

In conclusion, this study demonstrates that additive manufacturing provides a practical framework for developing affordable, reproducible, and educationally validated simulators for complex thoracic reconstruction. By combining 3D-printed molds with reusable silicone components, the proposed platform illustrates how additive manufacturing can extend beyond anatomical visualization to generate scalable simulation systems capable of supporting advanced surgical education.

CONCLUSIONS

A low-cost three-dimensional printed surgical simulator for bronchial and pulmonary vascular anastomosis training was successfully developed and validated. The model demonstrated favorable face validity, content validity, and construct validity among participants with different levels of surgical experience. Its reproducible manufacturing process and affordable cost make it a potentially accessible platform for deliberate practice of complex reconstructive procedures. Further studies are required to determine whether simulator-based training translates into improved operative performance and long-term skill acquisition.

Declarations

Ethical statement

The study was approved by the Navarra Clinical Research Ethics Committee (PI_2022/21), following the principles of the Declaration of Helsinki and current regional regulations.

Conflict of interest

The authors declare no conflicts of interest.

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Author Contribution

SLS prepared the manuscript draft and organized the study outline. SLS wrote the main manuscript text, incorporated revisions, and prepared figures. Methodology was done by all the authors. NLC, MLO, PA created the 3D printed models. VCS performed the data analysis and wrote the results. SLS reviewed the final draft and wrote the final version of the manuscript.

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and manufacturing phases of the simulator. Their contributions were essential to the successful completion of this project.

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Figures

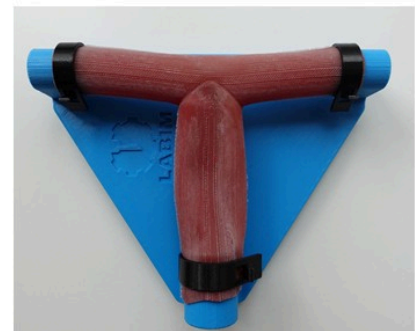


Figure 1

Computer-aided design and manufacturing process of the Pulmonary artery model.

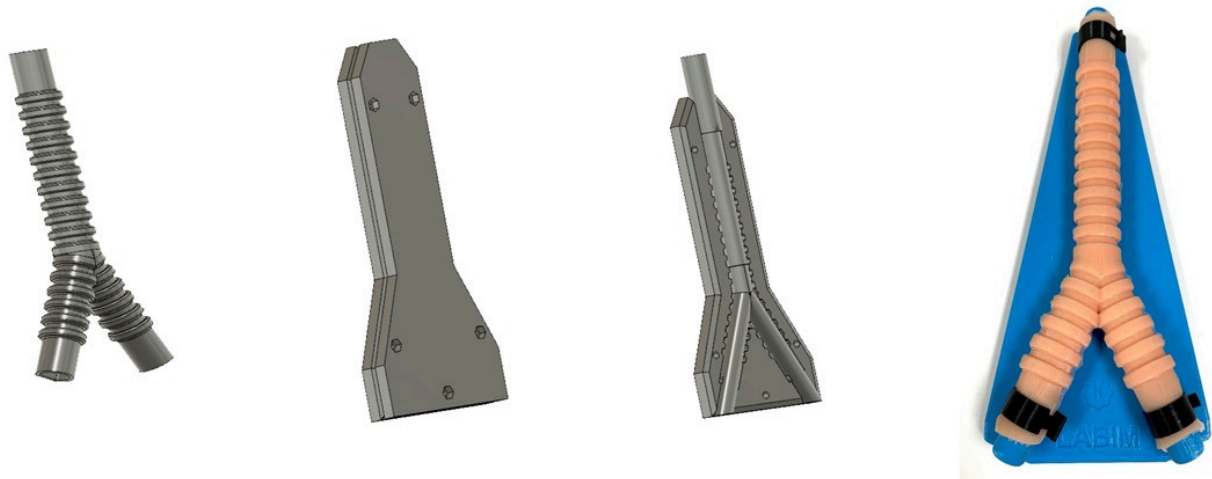


Figure 2

Computer-aided design and manufacturing process of the Bronchial model.



Figure 3

Final simulators models including the Thoracic platform.



Figure 4

Use of the simulators performing interrupted and continuous sutures on both airway and vascular models.

Supplementary Files

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