

Original Research

Development, Implementation, and Evaluation of a Novel Low-Cost, High Anatomical Fidelity 3D-Printed Tracheostomy Care Simulation Model in Rwanda

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Abstract

Introduction

Basic tracheostomy management is an essential skill for primary care practitioners, yet there is often limited training in formal medical education. This study aimed to develop and evaluate a low-cost, 3D-printed tracheostomy model to enhance simulation-based training and improve proficiency and confidence in airway management among general practitioners (GPs) in Rwanda, where prior research has identified gaps in training.

Materials and Methods

This two-phase study included expert validation by otolaryngologists followed by pilot testing of the model. Five local otolaryngologists evaluated the model's anatomical accuracy, clinical relevance, and training utility. Subsequently, 40 GPs from across Rwanda participated in a hands-on simulation workshop in Rwanda. Training focused on suctioning, tube replacement, neck tie placement, and managing accidental decannulation. Pre- and post-training surveys assessed changes in knowledge, confidence, skill, and perceived relevance. Procedural skills were independently evaluated through standardized video and rubric assessments.

Results

Otolaryngologists rated the model highly for accuracy, relevance, and cost-effectiveness. Each reusable 3D-printed tracheostomy simulation model was produced at a cost of \$32.22 USD, offering a sustainable and affordable alternative to commercial simulation tools in low-resource settings. During the training workshop, significant improvements were observed across all domains. Knowledge scores increased by 15% ($p < 0.001$), and confidence scores improved by +2.11 to +2.59 points ($p < 0.001$) on a 5-point scale. Objective skills ratings showed marked gains in tracheostomy technique (+2.55, $p < 0.001$) and post-care management (+2.90, $p < 0.001$).

Conclusion

This affordable, 3D-printed tracheostomy model effectively enhanced GP confidence, skills, and knowledge. The project highlights the value of context-appropriate simulation tools in strengthening clinical capacity in low-resource settings.

Keywords: Tracheostomy care, Airway management, Simulation training, 3D-printed medical models, Global surgery education, Low-resource settings, General practitioners, Clinical skills development, Surgical simulation

INTRODUCTION

Tracheostomy care is an essential aspect of airway management for patients requiring long-term ventilation or respiratory support, yet it remains a complex and critical procedure. In many resource limited settings, the primary care workforce which includes general practitioners (GPs) are vital in supporting tracheostomy management, particularly in emergencies and given the scarcity of otolaryngology subspecialists.¹ However, GPs in such settings often face substantial challenges in managing these procedures due to a number of factors including lack of formal training.^{1,2} Healthcare providers in low- and middle-income countries (LMICs) report low levels of comfort and confidence when performing critical airway management procedures, such as tracheostomy care.³⁻⁵ In a study conducted by Nyanzi et al. (2023), clinicians in Uganda reported inadequate training in tracheostomy management, leading to suboptimal care and increased risk for patients.⁶ Furthermore, healthcare providers in LMICs report limited access to specialized training more broadly, advanced equipment, and hands-on experience, leading to low confidence and competence in performing critical procedures such as tracheostomy management.⁷

Simulation-based training has emerged as a promising solution to address these gaps in clinical education. Low-cost, high-anatomical models are effective in improving healthcare workers' skills, confidence, and patient care outcomes.^{8,9} 3D-printed models have successfully simulated complex medical procedures such as cricothyrotomy, chest tube insertion, and temporal bone dissection, providing a safe, cost-effective alternative to traditional methods.¹⁰ The use of 3D-printed models in airway management training improved practitioners' technical skills, alleviated discomfort, and enhanced clinical knowledge, providing an effective means of knowledge sharing between providers and patients through hands-on practice in a controlled, risk-free environment.^{11,12}

This project seeks to develop a novel low-cost, high anatomical fidelity 3D-printed tracheostomy model to enhance simulation-based training for GPs in Rwanda. A competency-building tracheostomy training model holds promise for broader application across LMICs and low-resource healthcare environments as a tool to teach and reinforce essential management of tracheostomy care for all health care providers.

METHODS

Study Design

The development and evaluation of the 3D-printed tracheostomy model were conducted as a Type II effectiveness-implementation study, which simultaneously assessed the training's impact and evaluated implementation outcomes such as acceptability, feasibility, adoption, and cost. Additionally, the service outcome of effectiveness was evaluated through knowledge, confidence, and skill. The study was carried out in two phases: an initial pilot phase with subspecialists and a subsequent simulation training event for GPs from across Rwanda ([Figure 1](#)).

The pilot phase aimed to assess the acceptability and relevance of the model among local otolaryngologists, while the training event focused on evaluating the effectiveness of the model in improving tracheostomy management skills in a real-world training environment. These evaluated domains are summarized in [Figure 2](#).

Initial Review by ENT Providers

We first sought feedback from local ENT providers in Rwanda to ensure the model's accuracy and relevance to clinical practice. Five ENT practitioners evaluated the model based on its fidelity to real-life clinical scenarios, including its anatomical accuracy, functionality (such as the ability to perform suctioning, decannu-

lation, and tracheostomy replacement), and overall usability. The ENT providers completed a structured questionnaire that addressed 1) relevance to real-life scenarios, 2) anatomical accuracy, 3) usability, and 4) functionality. The feedback collected from the ENT providers served to refine the model to assess whether it met the needs of healthcare providers in Rwanda.

Simulation Training Event

Following the pilot phase, the model was tested in a simulation course for GPs on April 4-5, 2025, held at the University of Global Health Equity (UGHE) in Kigali, Rwanda. The event provided 40 GPs from around Rwanda with a hands-on opportunity to practice critical tracheostomy management skills using a 3D-printed model coupled with didactics and coaching from ENTs.

The simulation training focused on key aspects of tracheostomy care including accidental decannulation, suctioning, tracheostomy tube tie placement, and tracheostomy tube replacement. A pre- and post-training survey assessed changes in participants' knowledge, skill, comfort, and confidence in tracheostomy care. The survey consisted of demographics, knowledge, self-perceived skill, comfort/confidence, utility of training, and prior exposure (Supplemental Material). Additionally, participant performances were video recorded before and after training and then rated with a rubric. This rubric was adapted to assess the skills taught at our training and to the Rwandan health setting from the Objective Structured Assessment of Technical Skills (OSATS), which is commonly used to assess surgical skills, as well as existing airway management simulation assessment tools.¹³⁻¹⁵

Data Analysis

Data from the pre/post surveys were analyzed quantitatively using paired t-tests or non-parametric equivalents to assess significant differences in participants' knowledge, skill, and comfort levels before and after the intervention. Additionally, qualitative feedback from open-ended questions was analyzed thematically.

Ethical Considerations

The Rwandan Institutional Review Board at the Rwanda National Ethic Committee (RNEC) approved this study (study #: 00001497). All participants in the simulation training event provided written informed consent.

RESULTS

Participant Demographics

Forty GPs from across Rwanda participated in the ENT simulation training course held at the University of Global Health Equity (UGHE) in Kigali on April 4-5, 2025. Participant demographic data is summarized in [Table 1](#).

3D-Printed Model Development and Cost

The tracheostomy simulation model was produced using cost-effective materials, with a total production cost of \$136.50 total with a per unit cost of \$32.22 ([Table 2](#)). The model incorporated thermoplastic polyurethane (TPU) for airway structures over-molded inside of casted silicone for soft tissue simulation, seated in a polylactic acid (PLA) base. Additionally, reusable tracheostomy tubes, straps, and suction catheters were gathered to supplement the model and not included in the final cost analysis ([Table 2](#)).

The design and fabrication process was informed by resources available through the UCSF Makers Lab Project Repository, which documents similar applications of 3D printing for medical simulation models and training tools in low-cost, resource-limited settings ([Supplemental Material](#)).

Figure 1. 3D-Printed Tracheostomy Training Model

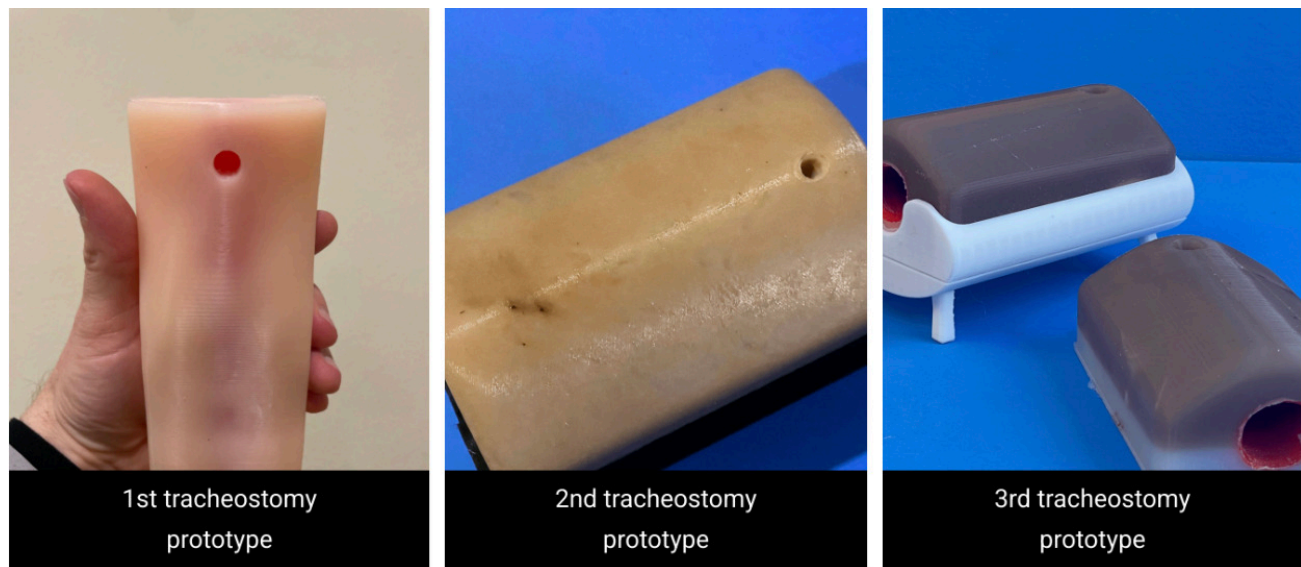


Figure 2. Evaluation of Training Outcomes Across Domains: Acceptability, Appropriateness, Costs, Feasibility, and Effectiveness

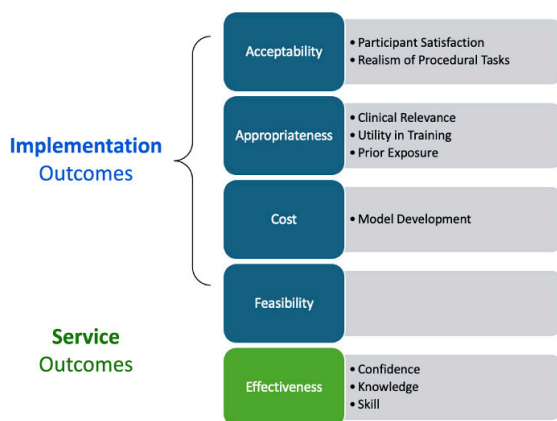


Table 1. Demographic Characteristics of General Practitioners Participating in the Tracheostomy Simulation Training (N = 40)

Characteristic	N (%)
Total Participants	40
Gender	
Male	27 (67.5)
Female	13 (32.5)
Average Age (years)	31.4
Average Years in Clinical Practice	3.47
Primary Workplace	
District Hospital	27 (67.5)
Teaching/Referral Hospital	10 (25)
Health Center/Health Post	2 (5)
Private Health Facility	1 (2.5)

Expert Evaluation

Five local otolaryngologists evaluated the model's anatomical accuracy, clinical relevance, procedural realism, and training utility (Table 3). The model received average expert ratings of 4.5-5 out of 5 across all domains. Feedback highlighted high anatomical fidelity and strong alignment with common clinical scenarios encountered by GPs in Rwanda. The model was noted for its affordability and practicality as a sustainable alternative to imported mannequins, with recommendations for minor durability refinements. Reviewers recommended minor durability refinements, including reinforcing high-stress areas around the stoma, improving the adhesion between the airway insert and silicone base, and considering replaceable silicone inserts at the tracheostomy site to extend the model's lifespan with repeated use.

Training Impact on Knowledge, Skill, and Confidence

Pre- and post-training participant self-assessments demonstrated statistically significant improvements in knowledge, procedural skills, and confidence (Table 4). Pre-training surveys indicated limited prior exposure to tracheostomy care, with low baseline confidence and procedural skill levels reported. Knowledge scores increased from 53.3% to 68.4% (+15%, $p < 0.001$). Confidence ratings across all management tasks improved substantially, with increases ranging from +2.11 to +2.59 points on a 5-point Likert scale ($p < 0.001$).

Objective skills assessments, conducted through an independent review of participant-recorded simulation videos, confirmed significant procedural skill improvements. Notable increases were observed in tracheostomy removal/insertion technique (+2.55 points, $p < 0.001$) and post-tracheostomy care (+2.90 points, $p < 0.001$), which included essential tasks such as suctioning to confirm tube patency, appropriate placement and tensioning of tracheostomy ties, and application of a dressing beneath the tracheostomy flange.

*Simulation Curriculum Feasibility

*Participants rated the simulation-based training highly for its clinical relevance and practical utility (Table 4). The 3D-printed model's affordability and procedural realism contributed to the program's feasibility for continued use in low-resource environments. Feedback supported incorporating simulation-based ENT education into ongoing professional development curricula.

This simulation-based tracheostomy management curriculum, supported by a novel 3D-printed model, enhanced general prac-

Table 2. Cost Breakdown for Development of 3D-Printed Tracheostomy Simulation Model

Item	Description	Unit Cost (USD)	Quantity	Total Cost (USD)
3D Printing Filament	Thermoplastic Polyurethane filament (TPU) used for model base and airway structures	\$8.87	5	\$44.35
3D Printed Mold	3D printed PLA mold	\$4.15	1	\$4.15
Silicone Insert Materials	Used for creating soft tissue and skin interface	\$15	5	\$75
Tracheostomy Tube (Reusable Demo)	Used in demonstration and replacement simulations	Donated	5	\$0
Tracheostomy Straps and Velcro (Reusable Demo)	For simulating securement of tracheostomy tube	Donated	5	\$0
Suction Catheters (Reusable Demo)	For simulating suctioning inside trachea and stoma	\$2.20	5	\$11
Miscellaneous Assembly Materials	Adhesive, fasteners, sanding tools/file	\$2	1	\$2
Total		\$32.22 per unit		\$136.50 total

Table 3. Expert Evaluation of the 3D-Printed Tracheostomy Simulation Model Based on Accuracy, Relevance, Usefulness and Efficacy

Evaluation Criteria	Average Expert Rating (1-5)*	Comments
Anatomical Accuracy	5 ($\pm$ 0.0)	The model accurately replicates the key anatomical features of the tracheostomy site, including the trachea, stoma, and surrounding structures.
Clinical Relevance	5 ($\pm$ 0.0)	The model's design and features are highly relevant to the procedures that GPs commonly perform in managing tracheostomies in Rwanda.
Utility in Training	4.5 ($\pm$ 0.5)	The model is valuable for training GPs, especially in skills like suctioning and tube replacement. Some minor adjustments for long-term durability may be needed: including reinforcing the region around the stoma to better withstand repeated tube insertions and removals, securing the interface between the airway lumen and surrounding silicone to prevent material separation over time, and exploring modular or replaceable silicone inserts at the tracheostomy site to reduce wear in high-use areas.
Efficacy in Skills Development	5 ($\pm$ 0.0)	The model is highly effective in helping participants develop critical skills, particularly in a simulated environment where hands-on practice is essential.
Realism of Procedural Tasks	5 ($\pm$ 0.0)	The simulation of tasks such as accidental decannulation, suctioning, and tube replacement is highly realistic and useful for training.
Cost Effectiveness	5 ($\pm$ 0.0)	The model is a cost-effective alternative to expensive commercial mannequins, making it suitable for resource-limited settings.
Overall Effectiveness	4.5 ($\pm$ 0.5)	The model is overall effective in achieving the training goals, including improving GPs' confidence and skill in managing tracheostomies.

*1: Poor, 2: Fair, 3: Good, 4: Very Good, 5: Excellent

tioners' knowledge, procedural skills, and confidence in airway management. Expert validation and participant feedback confirmed the model's clinical utility, affordability, and adaptability.

DISCUSSION

This study demonstrates that a novel, low-cost, anatomically realistic 3D-printed tracheostomy model, when paired with a structured curriculum and expert-led instruction, significantly improved general practitioner knowledge, perceived skill, and confidence in performing essential tracheostomy procedures. Feedback from local ENT providers confirmed the model's anatomical accuracy and clinical relevance, while GPs reported that the simulation training was both applicable and impactful in preparing them for real-world clinical scenarios. GPs are a criti-

cal cadre of care providers across Rwanda, given the availability of fewer than 30 ENT subspecialists for a population of over 13 million people.¹⁶ Importantly, the success of this project depended not only on the physical model but also on the design and delivery of the accompanying curriculum. Structured instruction, deliberate practice, and expert coaching were essential to maximizing the educational benefit, underscoring that the model and the curriculum should be viewed as equally critical components of the intervention.

In the simulation literature, fidelity is conceptualized along a spectrum encompassing physical, functional, and psychological realism.^{17,18} While our model does not incorporate the physiologic feedback or advanced features of high-fidelity simulators, it provides a higher degree of anatomical fidelity than many improvised, low-cost trainers currently used in low-resource settings.

Table 4. Participant Assessment Pre- and Post-Simulation Training on Key Domains

Domain	Pre-Training Evaluation (SD)	Post-Training Evaluation (SD)	Mean Change	P value
<i>Utility/Relevance</i>				
Otolaryngology skills are relevant to my clinical practice? (1- Strongly Disagree to 5- Strongly Agree)	4.41 (± 0.62)	-	-	-
Adequate otolaryngology training in medical school? (1- Very Inadequate to 5- Very Adequate)	3.33 (± 0.77)	-	-	-
<i>Knowledge</i>	53.3% (± 14.2)	68.4% (± 12.6)	+15%	<0.001
<i>Confidence</i>				
Assessing a patient with a tracheostomy	2.54 (± 0.85)	4.74 (± 0.45)	+2.20	<0.001
Suctioning a tracheostomy tube	2.72 (± 0.89)	4.53 (± 0.60)	+2.11	<0.001
Managing an obstructed tracheostomy tube	2.13 (± 0.76)	4.59 (± 0.58)	+2.46	<0.001
Performing an emergency tracheostomy change	1.72 (± 0.71)	4.31 (± 0.63)	+2.59	<0.001
Identifying and managing tracheostomy-related complications	1.82 (± 0.65)	4.10 (± 0.70)	+2.28	<0.001
<i>Prior Exposure</i>				
Have you ever completed an emergency tracheostomy change in clinical practice? (1-Never to 4- Many Times)	1.21 (± 0.49)	-	-	-
How often do you see tracheostomy patients in your practice? (1-Never to 4- Many Times)	2.33 (± 0.72)	-	-	-
How often do you do tracheostomy management in your clinical practice beyond emergency tracheostomy changes? (1-Never to 4- Many Times)	1.36 (± 0.59)	-	-	-
<i>Skill*</i>				
Patient/Provider Positioning	4.21 (± 0.570)	4.90 (± 0.30)	+0.69	<0.01
Tracheostomy Removal/Insertion Technique	2.19 (± 0.81)	4.74 (± 0.44)	+2.55	<0.001
Post Tracheostomy Placement Care	1.2 (± 0.56)	4.10 (± 0.68)	+2.90	<0.001
Knowledge of Specific Procedure	1.95 (± 0.64)	3.95 (± 0.65)	+2.00	<0.001

*Skill was evaluated by an independent reviewer (N.P.) who assessed pre- and post-assessment participant videos of tracheostomy management task completion

Accordingly, it is best classified as a low-fidelity but high-anatomical fidelity, low-cost task trainer. While prior studies have explored the use of both high-fidelity mannequins and lower-fidelity task trainers for airway management training in LMICs, many of these models remain prohibitively expensive or lack anatomical realism.^{1,2,10} Existing low-fidelity, low-cost models are driven by local initiatives and resource constraints.¹⁹ These models facilitate skills improvement and confidence but often lack the anatomical accuracy needed for more formal skill acquisition and confidence building for GPs.^{20,21} On the other hand, high-fidelity, high-cost models offer greater anatomical detail and more comprehensive simulation capabilities but higher costs may make them inaccessible to a wider population of learners.²² In global health practice, low-fidelity trainers are often more practical due to their affordability, reproducibility, and ease of local implementation. Our project exemplifies how such models can be designed to balance realism with cost, offering a feasible, sustainable solution for procedure-based training in LMIC contexts.

Participants emphasized the importance of ongoing access to the model at their healthcare facilities for deliberate practice, particularly in remote district hospitals with limited ENT or anesthesia support. Prior literature has established that simulation-based learning is most effective when combined with structured instruction, deliberate practice, expert coaching, and opportunities for feedback.^{9,11} Moving forward, continuing to integrate this model with a comprehensive airway management curriculum, inclusive of didactic content, emergency algorithms, and coaching from experienced providers, will be critical to maximizing its educational impact and sustaining long-term competency gains.

Beyond formal training workshops, participants asked for permanent access to the model at their healthcare facilities for ongoing practice, particularly valuable in remote district hospitals with limited ENT or anesthesia support. Additionally, several providers highlighted the potential utility of the model for patient and caregiver education, offering a tangible tool to explain tracheostomy care procedures to families.^{23,24} Broader dissemination of the model, contingent on the affordability of local printing resources, could enhance airway management capacity not only for providers in training but also for community health education initiatives.

While this study demonstrates significant immediate improvements in knowledge, skills, and confidence following simulation training with the 3D-printed tracheostomy model, it does not assess long-term retention of these gains. It is well recognized that initial post-training improvements may diminish over time without ongoing practice or reinforcement. Future research should include longitudinal follow-up to evaluate the durability of skills and knowledge retention among general practitioners. Additionally, while the model showed strong expert validation and positive participant feedback, further studies could explore scalability across diverse healthcare settings and its impact on actual clinical outcomes. Importantly, capturing more formal user-centered feedback on prototype usability and suggestions for improving sustainability through open ended exit interviews would strengthen the model's relevance and acceptability, particularly if the training program is repeated or scaled up in the future. Finally, the sample size was limited to GPs in Rwanda, and findings may not generalize fully to other contexts or healthcare systems.

CONCLUSION

This project demonstrates the value of a low-fidelity, high-anatomical fidelity, low-cost 3D-printed tracheostomy task trainer as part of a structured simulation curriculum for healthcare providers in resource-limited settings. When combined with deliberate practice, expert coaching, and curricular reinforcement, the model significantly improved GP knowledge, skills, and confidence in tracheostomy management. Its affordability and ability to be produced locally make it a practical and sustainable option for expanding airway management training capacity in LMICs. These findings highlight the potential of low-fidelity but anatomically realistic models to complement comprehensive training curricula, enhance clinical competencies, and improve the quality of care for patients requiring tracheostomy.

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Conflict of Interests

None

Author Contributions

NP: development of model, project design, data collection, data analysis, manuscript drafting, manuscript editing

KP: data collection, curriculum development, manuscript editing and revisions

GC: manuscript editing and revision, skills rubric development

SD: development and refinement of model, manuscript editing

JB, HN, AH, AK, DS: training instruction, model refinement, manuscript editing and revision

CN, IN, JN, DN, GN, EU: manuscript editing and revision

NM, JA, OM: manuscript editing and revision, curriculum and training coordination

MJX, GT: project design, model refinement, manuscript drafting, manuscript editing, project oversight

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SUPPLEMENTARY MATERIALS

Trach_Sim_Rubric_Supplemental_Material_1

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