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Evaluation of a low-cost, 3D-printed model for bronchoscopy training

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Abstract

Background: Flexible bronchoscopy is a fundamental procedure in anaesthesia and critical care medicine. Although learning this procedure is a complex task, the use of simulation-based training provides significant advantages, such as enhanced patient safety. Access to bronchoscopy simulators may be limited in low-resource settings. We have developed a low-cost 3D-printed bronchoscopy training model.
Methods: A parametric airway model was obtained from an online medical model repository and fabricated using a low-cost 3D printer. The participating physicians had no prior bronchoscopy experience. Participants received a 30-minute lecture on flexible bronchoscopy and were administered a 15-item pre-test questionnaire on bronchoscopy. Afterwards, participants were instructed to perform a series of predetermined bronchoscopy tasks on the 3D printed simulator on 4 consecutive occasions. The time needed to perform the tasks and the quality of task performance (identification of bronchial anatomy, technique, dexterity, lack of trauma) were recorded. Upon completion of the simulator tests, participants were administered the 15-item questionnaire (post-test) once again. Participant satisfaction data on the perceived usefulness and accuracy of the 3D model were collected. A statistical analysis was performed using the t-test. Data are reported as mean values (± standard deviation).
Results: The time needed to complete all tasks was 152.9 ± 71.5 sec on the 1st attempt vs. 98.7 ± 40.3 sec on the 4th attempt ($P = 0.03$). Likewise, the quality of performance score improved from 8.3 ± 6.7 to 18.2 ± 2.5 ($P < 0.0001$). The average number of correct answers in the questionnaire was 6.8 ± 1.9 pre-test and 13.3 ± 3.1 post-test ($P < 0.0001$). Participants reported a high level of satisfaction with the perceived usefulness and accuracy of the model.
Conclusions: We developed a 3D-printed model for bronchoscopy training. This model improved trainee performance and may represent a valid, low-cost bronchoscopy training tool.

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Key words: flexible bronchoscopy, education, simulation, 3D printing

Flexible bronchoscopy is a common and life-saving procedure in anaesthesia, as well as emergency and critical care medicine. Learning this procedure is a complex task, which encompasses heterogeneous and multifaceted components. These include the following knowledge components: understanding of airway anatomy; indications and contraindications; common complications; equipment setup; along with a practical component of the acquisition of psychomotor skills that require development of hand-eye coordination [1]. As with other invasive clinical procedures, the use of simulation-based training has the potential to provide significant advantages finally leading to enhanced

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patient safety, and has been proven to be superior to training that did not include simulation in many specific outcomes including skills, behaviour and time [2, 3].

Furthermore, even low-fidelity simulators have proved to be effective, and in certain areas, such as basic bronchoscopy tasks, they may indeed be superior to high-fidelity computerized simulators [4].

Unfortunately, simulators are generally very expensive [5]. Access to such tools may be limited in low-resource settings, therefore limiting the learning opportunities for healthcare professionals in such environments.

We developed a low-cost, highly portable model for bronchoscopy training, using a low-cost 3D-print of a normal tracheo-bronchial tree modified using free software from an online medical repository model.

The aim of this mannequin study is to test whether this newly developed bronchoscopy simulator could be used to improve the procedural understanding and skills of trainees.

METHODS

MODEL

A parametric airway model was derived from an online medical model repository (http://lifesciencedb.jp/bp3d/). The parametric airway was separated into seven distinct regions: trachea, bifurcation, left & right bronchi and primary bronchi to the upper left, lower and middle right lobes within free 3D modelling software, namely Meshmixer (Autodesk, Inc. San Rafael, CA, USA). Anatomical regions were printed with different colours using polylactic acid (PLA) thermoplastic 3D printing filament printed on a fused deposition modelling 3D printer (Series 1 Pro, Type A Machines, San Leandro, CA, USA). In total, the model required approximately 9 hours to print and assemble all the necessary distinct regions of the airway. The total estimated cost of raw materials required to create all seven pieces for the full airway model was approximately $5.00 USD. The model was then enclosed in a carton to ensure blinding of the structures to participants, with the trachea extruding through a side-hole and intubated with a size 8.0 mm endotracheal tube (Rusch, Teleflex Medical Europe Ltd., Athlone, Co. Westmeath, Ireland) (Fig. 1).

SUBJECTS

Institutional review board approval was obtained. The subjects represented a convenience sample of staff intensive care physicians who self-reported no previous experience with bronchoscopy, and who provided consent to participate in the study.

STUDY DESIGN

Participants received an introductory 30-minute lecture on flexible bronchoscopy that included the following: bronchoscopic anatomy; description of the instrument; technique; indications; contraindications; and complications.

They were then administered a 15-item questionnaire on bronchoscopy derived and modified from the different modules of bronchoscopy training from a web-based curriculum [6], previously utilized as a useful test of bronchoscopic knowledge (see: appendix A) [7, 8].

Following the pre-test questionnaire, participants were separately invited to use the flexible bronchoscope (Olympus, Tokio, Japan) on the model, and instructed to perform a series of predetermined tasks in 4 consecutive rounds. These tasks consisted in navigating the bronchial tree to visualise specific bronchial segments. The time needed to perform the tasks (from insertion of the bronchoscope into the endotracheal tube to completion of the task) and the quality of task performance (based on a standardised score assessing one's ability to visualize a specific segment; technique and dexterity; lack of trauma) were recorded by one of the investigators (see: appendix B) [9, 10]. After completion of the mannequin tests, participants were administered the 15-item questionnaire (post-test) once again. Participants' satisfaction data on the perceived usefulness and accuracy of the model were collected.

A statistical analysis was performed using Student's t-test. Data are reported as mean values ± SD.

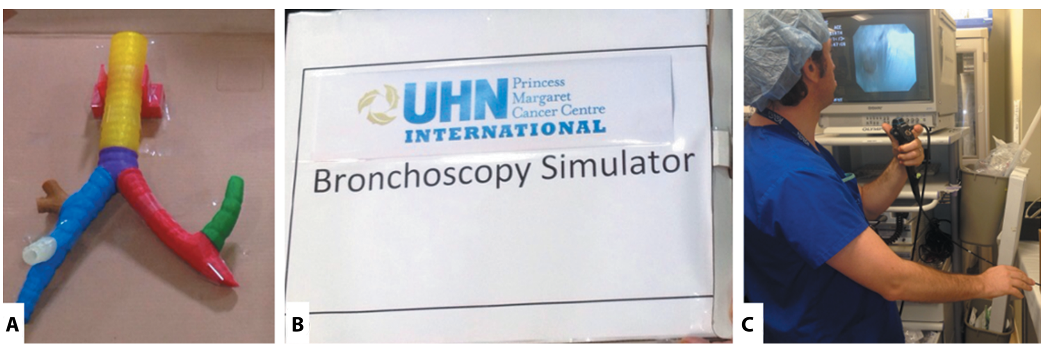

Figure 1. The 3D-printed bronchoscopy model. A view of the 3D-printed tracheo-bronchial tree with materials of different colours **(A)**; the carton containing the model, designed to blind participants to the trachea-bronchial tree **(B)**; the simulator in use with a bronchoscope **(C)**

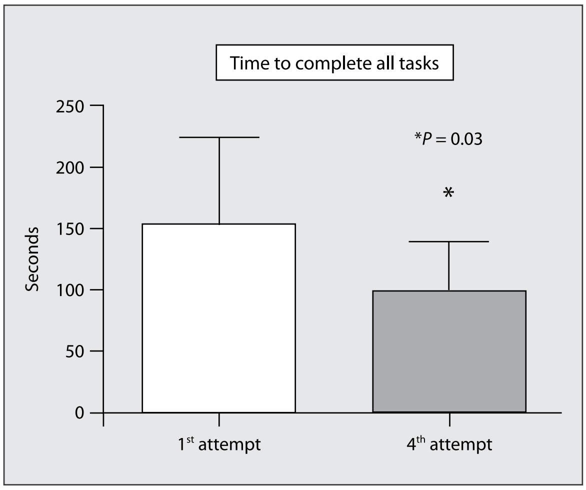

Figure 2. Time needed to complete all requested tasks on the bronchoscopy simulator on the first and last attempt

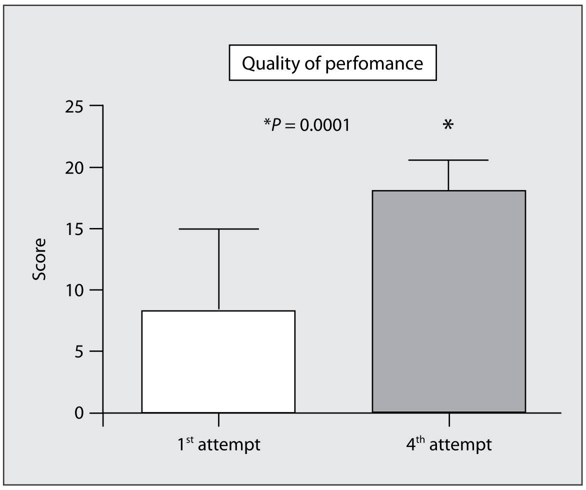

Figure 3. Bronchoscopy performance score on the simulator on the first and last attempt

RESULTS

The time needed to complete all the requested tasks was 152.9 ± 71.5 sec on the first attempt vs. 98.7 ± 40.3 sec on the fourth attempt ($P = 0.03$) (Fig. 2). The quality of task performance score improved from 8.3 ± 6.7 on the first attempt to 18.2 ± 2.5 ($P < 0.0001$) (Fig. 3). The average number of correct answers in the questionnaire was 6.8 ± 1.9 pretest and 13.3 ± 3.1 post-test ($P < 0.0001$). The participants reported a level of high satisfaction with the perceived usefulness and accuracy of the model.

DISCUSSION

We developed a 3D-printed model for bronchoscopy training in a remote area as part of an international academic collaboration. This is a simple model of the infraglottic airway that is aimed at improving recognition of pertinent anatomical structures and facilitating acquisition of dexterity skills. In our study, practice with the model improved trainees' performance, and may represent a valid, low-cost addition to the learning of this important procedural skill.

To our knowledge, this is the first test on a 3D-printed model designed to serve such a purpose. Byrne *et al*. [11] recently published a description of the creation of a 3D-printed bronchoscopy training system from an actual patient tomography scan and, similarly to what we observed, reported a high degree of anatomic fidelity. To our knowledge, no data regarding the testing of the device in the practice of bronchoscopy have been published yet.

Although several experts emphasise the importance of a volume-based approach to procedural competency, this appears to be difficult to achieve in many training programs [12]. Indeed, teaching invasive techniques in the clinical setting is a challenging task, with many contributing factors that include, among others, concerns about patient safety, learner's anxiety, as well as time and production pressure [7]. To overcome such difficulties, the use of simulation-based teaching has gained increasing popularity in recent years, as well as due to improving technology that has facilitated the reproduction of realistic scenarios.

Bronchoscopy has benefitted from the introduction of simulators which have shown to facilitate learning and to improve performance compared to training opportunities that did not include simulation [13]. Interestingly, these advantages were well preserved, even when so called low-fidelity simulators were used [13].

Unfortunately, simulators are relatively expensive and may not be widespread and easily accessible. These aspects may become particularly problematic in limited-resource settings, where constraints concerning cost and accessibility to teaching sessions are responsible for further reductions in training opportunities. Our 3D-printed simulator may serve all these settings well, given its efficacy, portability, fidelity and low costs. Furthermore, this model is intended for use with real bronchoscopes, i.e. it allows a clinician to acquire dexterity on the use of the same tools that they will have available for patient care.

In our study, we modified an already-segmented anatomical 3D model freely available online to enhance the teaching experience. The model could have been 3D printed in a single colour on a low-cost desktop 3D printer, or online.

The availability of open access free online repositories of CT-based 3D anatomical models is increasing, along with the availability of public and online low-cost 3D printers. This allows medical educators to easily obtain accurate 3D printed parts to be used for multiple teaching scenarios.

A potential added benefit of such a model is that it can also be developed from CT scan-acquired images. Hence, it could also provide a 3D reconstruction of pathological conditions, offering one the opportunity to train on unique bronchoscopic findings in such diseases. The possibility to print in materials of different colours could also facilitate a more realistic rendering of such clinical conditions and/or enhance teaching by aiding the recognition of key structures/findings. These could offer significant advantages over many of the currently available bronchoscopy simulators, which are fixed model typically representing normal bronchial anatomy.

Our study has several limitations that are necessary to mention. First, it is an *in vitro* only assessment of performance. Therefore, even if trainees' performance improved over time, we are unable to address whether the benefit shown by the practice on the mannequin will translate into improved skills in vivo. Although previous studies reported a good correlation between skills gained *in vitro* and performance *in vivo* [4], the relationship between the use of our model and clinical performance will need to be evaluated in the future.

Secondly, we have not explored knowledge/skills retention after simulation training. Further studies are needed to assess this aspect and to evaluate the potential role of repeated uses of our model on the maintenance of acquired skills, as well as on refresher courses, in particular, in settings were clinical practice is limited. Thirdly, as our model was designed as comprising airways distal to the larynx, no test was performed on navigation of the upper airways.

It should be noted that we tested theoretical knowledge on bronchoscopy based on a multiple-choice questionnaire. Although we showed improved performance in the post-test questionnaire, we did not design the study and the questionnaire to specifically prove a correlation between mannequin practice and theoretical knowledge gained. Thus, many factors could have influenced the participants' performance on the questionnaire, such as a pre-/post--effect (i.e., the performance improved post-test, simply in light of the pre-test exposure). It is, however, possible that appreciation of particular aspects of bronchoscopy during one's practice on a mannequin may have at least in part facilitated the understanding of pertinent theoretical concepts.

CONCLUSIONS

We tested a new low-cost model for bronchoscopy training. This seems to be an effective tool to aid in the acquisition of this important procedural skill. Further studies are needed to understand the effect of training on this model on in vivo performance, as well as on knowledge retention.

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3. Sources of funding: The Lynn & Arnold Irwin Foundation, Toronto, ON, Canada.
4. Conflicts of interest: none.

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Appendix A

Questionnaire used for pre- and post-knowledge test (the correct answers are identified in bold)

Question 1: According to American Thoracic Society Guidelines, which of the following is an absolute contraindication to flexible bronchoscopy:

A. Patient with unstable asthma or status asthmaticus.

B. Patient with refractory hypoxemia or inadequate oxygenation during the procedure

C. Recent or unstable angina or recent myocardial infarction

D. Severe hypercarbia and significantly reduced forced expiratory volume in one second

E. Superior vena cava obstruction

Question 2: Originally, the flexible bronchoscope was designed to be held as shown in the figure below. A reason for this is:

A. The operator must always stand behind the patient; therefore it is best for the control section to be held in the left hand

B. Dr. Ikeda, original designer of the flexible bronchoscope, was left-handed

C. The operator must always stand to the right of the patient; therefore, it is best for the control section to be held in the left hand so that the bronchoscopist's right hand can be closest to the patient

D. The operator must always stand to the left of the patient; therefore, it is best for the control section to be held in the left hand so that the bronchoscopist's right hand can be closest to the patient

Question 3: Maximum flexion of the distal bending tip of the flexible bronchoscope is obtained by which of the following:

A. Moving the thumb upwards

B. Moving the thumb downwards

Question 4: Each of the following is considered "poor technique" when handling a flexible bronchoscope except

A. Twisting the insertion tube rather than rotating the entire instrument along its entire longitudinal axis.

B. Advancing the bronchoscope by pushing down from the handle.

C. Exerting excessive pressure with one's fingers on the patient's nostril or cheek.

D. Attempting to pass an instrument through a fully flexed distal extremity of the bronchoscope

E. Keeping the bronchoscope "in the midline" of the airway lumen throughout as much of the procedure as possible.

Question 5: When referring to digital photography, video imaging, television, or fluoroscopic image intensifiers, the term "resolution" is defined as:

A. Number of pixels per square centimeter

B. Number of lines per inch or line pairs per millimeter

C. Brightness of an image on screen

D. Sharpness of an image on screen

Question 6: When referring to digital photography, video imaging, television, or fluoroscopic image intensifiers, the term "resolution" is defined as:

A. Universal cord section

B. Control section

C. Light guide connector section

D. Eyepiece (or video) section

E. Insertion tube section

Question 7: What happened to the flexible bronchoscope shown in the figure:

A. It was bitten

B. It was caught in the drawer of a procedure cart

C. It was squeezed by an angry bronchoscopist

Question 8: Which of the following positions is inelegant and risks damaging the flexible bronchoscope?

A. Pushing downwards on the bronchoscope so that a bend forms in the insertion tube

B. Standing up straight, shoulders back, weight equally distributed on both feet

C. Sitting on a stool, keeping the insertion tube straight at approximately patient height

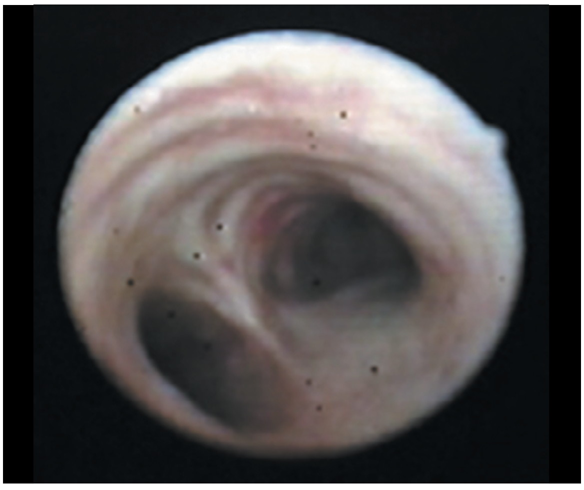
Question 9: When looking through the eyepiece of a flexible bronchoscope you notice that multiple small black dots are visible. This means that:

A. Water has leaked into the bronchoscope

B. The bronchoscope has been excessively exposed to radiation

C. Multiple fiberoptic bundles are broken

D. The bronchoscope needs to be replaced



Question 10: In a tall adult male patient with normal airways, a standard flexible bronchoscope occupies approximately what percentage of cross-sectional area of the trachea:

A. 5 percent

B. 10–15 percent

C. 20–25 percent

D. more than 25 percent

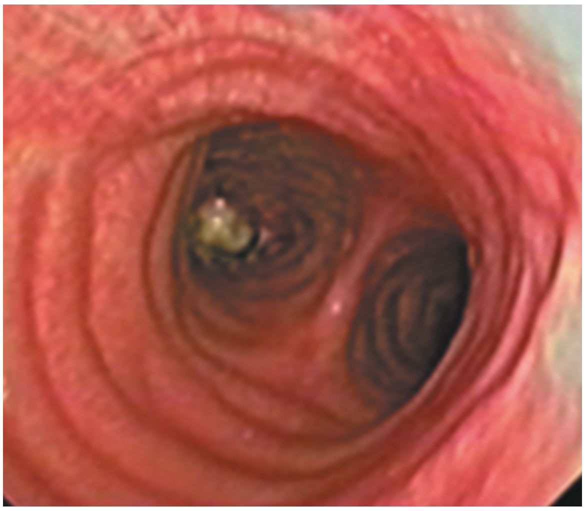
Question 11: Bronchoscopy is performed in a patient with cough and partial unilateral atelectasis. Based on the findings shown below, bronchoscopic examination should proceed with:

A. Examination of the left bronchial tree, then inspection and biopsy of the lesion on the right

B. Inspection and biopsy of the lesion on the right, then examination of the left bronchial tree

C. Examination of the right bronchial tree, then inspection and biopsy of the lesion on the left

D. Inspection and biopsy of the lesion on the left, then examination of the right bronchial tree



Question 12: While intubating a patient over the flexible bronchoscope, it suddenly becomes difficult to advance the bronchoscope. Although you are able to see the vocal cords, it is impossible to advance the endotracheal tube over the bronchoscope. What happened and what should you do next?

A. The bending tip of the bronchoscope broke. You remove the bronchoscope from the endotracheal tube

B. The tip of the bronchoscope has accidentally passed through the Murphy eye of the endotracheal tube. You remove the scope and the tube together as an ensemble

C. The polyurethane covering of the bronchoscope has slipped and intussuscepted over itself, occluding the endotracheal tube lumen. You remove the bronchoscope from the endotracheal tube

D. The tip of the bronchoscope is flexed too much and the endotracheal tube is caught in the aryepiglottic fold. You partially withdraw the endotracheal tube over the bronchoscope

Question 13: All of the following airway dimensions in the adult are correct except:

A. The left lower lobe bronchus beyond the origin of the superior segment is usually 1 cm in length before giving rise to the basal segmental bronchi.

B. The usual length of the trachea (distance from the cricoid cartilage to the main carina) ranges from 9–15 cm.

C. The usual internal caliber of the trachea ranges from 1.2–2.4 cm.

D. The right upper lobe bronchus is usually located about 1.5–2.0 cm below the main carina.

E. The usual length of the bronchus intermedius ranges from 2–4 cm beyond the origin of the right upper lobe bronchus.

Question 14: How would you describe the trachea shown in the figure below?

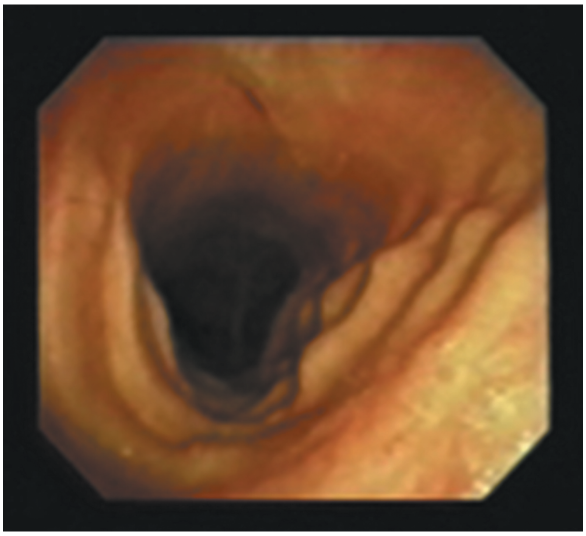
A. Normal C-shaped

B. Normal U-shaped

C. Normal horseshoe-shaped

D. Abnormal saber-shaped

E. Abnormal Lunate shaped



Question 15: It is most likely that the patient with this abnormal airway seen in the figure has which one of the following disorders:

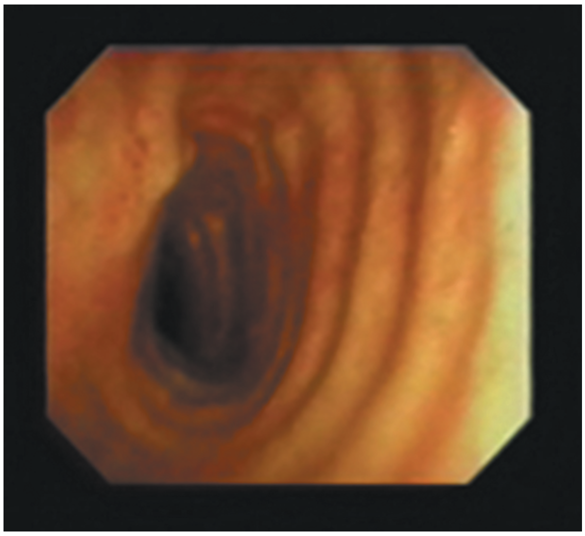
A. Sarcoidosis

B. Relapsing polychondritis

C. Teratoma with extrinsic tracheal compression

D. Underlying chronic obstructive pulmonary disease

E. Pulmonary amyloidosis



Appendix B

Data collection form used to record participants' performance on the simulator

A low cost, 3Dprinted model for bronchoscopy training
Data collection form

Study subject# ____________________

Attempt# ____________________

1. **Able to identify and enter all segments on the right:**
   a. RUL
   b. RML
   c. RLL
2. **Able to identify and enter all segments on the left:**
   a. LUL
   b. LLL
3. **Able to enter RUL, RML, RLL and LUL, LLL on request:**
   a. Unsatisfactory
   b. Needs improvement
   c. Satisfactory
4. **Time to perform tasks on point 3:**
   a. RUL ________ seconds
   b. RML ________ seconds
   c. RLL ________ seconds
   d. LUL ________ seconds
   e. LLL ________ seconds
5. **Able to keep scope centered and to avoid excessive trauma:**
   a. Unsatisfactory
   b. Needs improvement
   c. Satisfactory
6. **Able to maintain a good posture, hands position, equipment handling:**
   a. Unsatisfactory
   b. Needs improvement
   c. Satisfactory

Abbreviations:

RUL — right upper lobe; RML — right middle lobe; RLL — right lower lobe; LUL — left upper lobe; LLL — left lower lobe

RATING INSTRUCTIONS

	Performance parameter	Unsatisfactory	Needs improvement	Satisfactory
Items 1–3, 5 (each with 0–4 points)	Identification of anatomy (items #1–3)	No or little knowledge	Identified at least 50% of landmarks	Identified all landmarks
	Scope manipulation (#4)	Frequently pointing away from lumen; more than 5 episodes of trauma	Scope centered for most part; rare (< 5) episodes of trauma	Scope always centered; no episodes of trauma
Item 6	Posture, hand positions and equipment handling	Repeated attempts; clumsy; uncertain	Able to position oneself and use instrument although awkward at times	Comfortable, able to adjust hand position and posture, able to use instrument

GRADES

Item	Unsatisfactory (0)	Needs improvement (2)	Satisfactory (4)
1			
2			
3			
4			
5			
TOTAL			

TOTAL SCORE ________________