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Development and Initial Evaluation of a Novel, Ultraportable, Virtual Reality Bronchoscopy Simulator: The Computer Airway Simulation System

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BACKGROUND: Virtual reality (VR) simulation is an effective and safe method of teaching bronchoscopic skills. Few VR bronchoscopy simulators exist; all are expensive. The present study aimed to describe the design, development, and evaluation of a new, affordable, VR bronchoscopy simulator.

METHODS: Anesthesiologists and engineers collaborated to design and develop the Computer Airway Simulation System (CASS), an iPad-based, high-fidelity, VR bronchoscopy simulator. We describe hardware and software development, as well as the technical and teaching features of the CASS. Twenty-two senior anesthesiologists evaluated various aspects of the simulator (using a 5-point Likert scale) to assess its face validity.

RESULTS: Anesthesiologists performed a simulated bronchoscopy (mouth to carina) with a median (range) procedural time of 66 seconds (30–96). The simulator's ease of use was rated 4.3 ± 0.8 and the bronchoscope proxy's handling 4.0 ± 0.7. Criticisms included that excessive system reactivity created handling difficulties. Anatomical accuracy, 3-dimensional bronchial segmentation, and mucosal texture were judged to be very realistic. The simulator's usefulness for teaching and its educational value were highly rated (4.9 ± 0.3 and 4.8 ± 0.4, respectively).

CONCLUSIONS: We describe the design, development, and initial evaluation of the CASS—a new, ultraportable, affordable, VR bronchoscopy simulator. The simulator's face validity was supported by excellent assessments from senior anesthesiologists with regard to anatomical realism, quality of graphics, and handling performance, even though some future refinements are required. All the practitioners agreed on the significant educational potential of the CASS. (Anesth Analg 2019;129:1258–64)

KEY POINTS

- **Question:** Description of design, development, and face validation of a novel, affordable virtual reality bronchoscopy simulator.
- **Findings:** Report on the successful development of a virtual reality bronchoscopy simulator and its positive evaluation by senior anesthesiologists.
- **Meaning:** This new simulator will likely represent an affordable and effective tool with which to teach, train, and maintain bronchoscopic skills.

Flexible fiberoptic bronchoscopy is an invasive medical procedure that requires technical skill and hand–eye coordination. Bronchoscopic examination is commonly performed by physicians of various specialities. Indications for the procedure range from the diagnosis of airway diseases to the identification of tracheal tube positioning and assistance with tracheal intubation in the management of difficult airways. Interventional pulmonary procedures represent >500,000 flexible bronchoscopies per year in the United States,[1,2] and fiberoptic-assisted intubation is part of most difficult-airway algorithms.[3,4]

Depending on the indication, the number of procedures necessary before mastering the technique ranges from 10 to 20 for tracheal intubation to 100 for pulmonary diagnosis and procedural management.[1,5–7] Device handling, anatomical knowledge, and mastery of treatment procedures have all been identified as issues requiring competency,[8] and a specific learning curve has been demonstrated during training.[9] Although complications during bronchoscopy are rare, they can be life threatening,[10] with studies demonstrating an inverse relationship between operator experience and complication rates.[11,12]

Training for invasive medical procedures such as bronchoscopy is traditionally based on the apprenticeship method.[13] In the past decade, restrictions on working hours and increased numbers of trainees have reduced training

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opportunities and raised growing concerns about patient safety. Traditional teaching methods are now being challenged, and simulation-based medical education may offer an efficient adjunct. The chance to undergo effective, repeated training using simulation tools in a risk-free environment is a powerful aid to medical education.[14,15] For bronchoscopy, in particular, simulation-based training has been shown to be effective in improving trainees' skills and behaviors.[16,17]

Few validated virtual reality (VR) bronchoscopy simulators exist on the market.[18–20] All consist of a proxy bronchoscope and a robotic interface equipped with sensors that track the real-time motions of the bronchoscope and display them on a 3-dimensional airway model on a computer screen. Technical specificities vary between individual simulators, such as haptic and auditory feedback, a detailed objective assessment of the trainee's performance and skills, or various anatomical scenarios, for example. However, 1 common characteristic of currently available simulators is their high cost, with prices typically ranging from USD 25,000 to >USD 100,000, therefore limiting their widespread use. More affordable yet equally effective alternatives are thus needed. This technical report's goal is to describe the steps in the design of an affordable, ultraportable, computerized VR bronchoscopy simulator and to describe the first results and assessments of its face validity by senior anesthesiologists.

METHODS

The local Institutional Ethics Committee (Comitato etico cantonale Canton Ticino, 6501 Bellinzona) waived the requirement for written informed consent, in line with Switzerland's national guidelines for clinical research.

Cardiocentro Ticino's Department of Cardiac Anesthesia and Intensive Care in Lugano, Switzerland, in partnership with an engineering company (E-clectic SA, Lugano, Switzerland), designed and built an affordable but high-fidelity VR bronchoscopy simulator called the Computer Airway Simulation System (CASS). The project was conducted in collaboration with the Departments of Anesthesiology of the University Hospitals of Lausanne and Geneva, Switzerland, and was supported financially by the Foundation for Cardiological Research and Education and the FLAVA Foundation (Fondation Latine des Voies Aériennes, www.flava.ch).

Issues such as users' requirements, software, computer processing power, and hardware design were identified and addressed in stages.

Several characteristics were determined to be mandatory for the new simulator: minimal cost (<USD 5000) of the final product to ensure widespread uptake; ease of use and ultraportability (lightweight, compact design enabling usage in varied locations, such as medical classrooms, operating rooms, or training centers); a realistic proxy bronchoscope (size, shape, and feeling during use); realistic handling with regard to the system's reactivity; haptic feedback in case of collisions against the mucosa; high-quality anatomical accuracy of the 3-dimensional model of the airways; a complete anatomical model allowing a bronchoscopic examination starting from the nose or the mouth through the pharynx, larynx, and complete tracheobronchial tree down to the subsegmental bronchi; modularity of the 3-dimensional model allowing for future modifications and the creation of pathological or difficult anatomies; integration of educational tools in the software for continuous bronchoscope localization through the tracheobronchial tree, thus helping to teach airway anatomy and spatial orientation; and objective, automatic metrics, and feedback on the trainee's performance (total training time, time to reach different anatomical targets, number of collisions with the mucosa).

Development Phase

After 2 years of intensive work, the first fully functional prototype CASS was completed. The simulator's different components and the final CASS in use are shown in Figure 1A, B.

Hardware

Proxy Bronchoscope and the Robotic Patient Interface Device. To keep expenses to a minimum, we focused on building the proxy bronchoscope and its robotic patient interface using affordable,

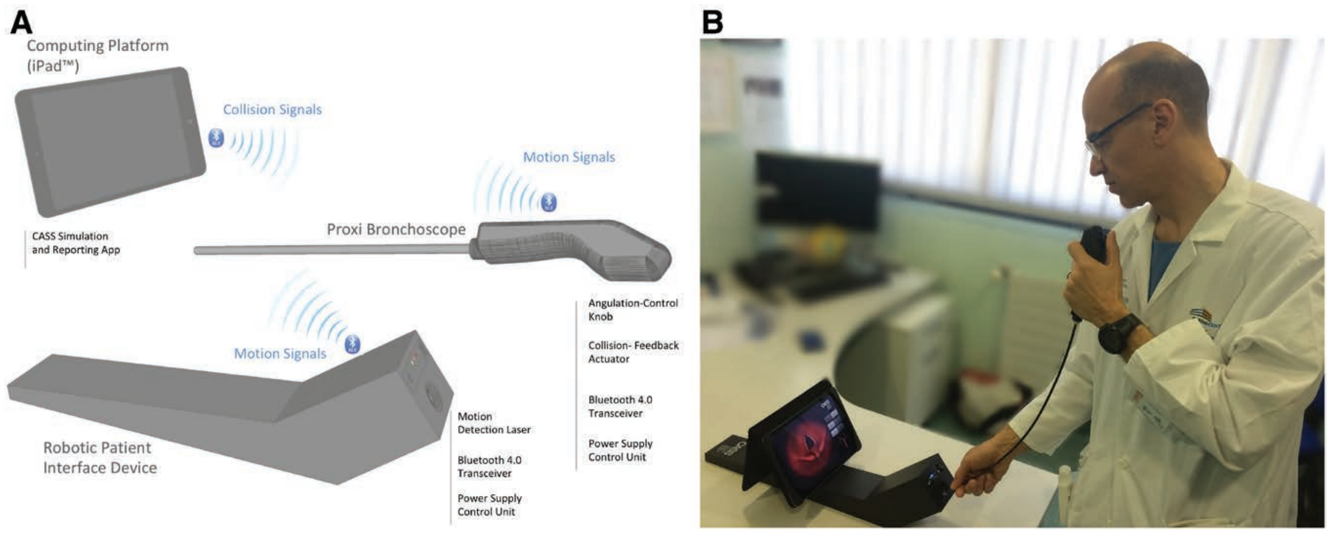

Figure 1. A, Technical components of the Computer Airway Simulation System (CASS). B, The CASS in use.

existing electronic components. Mechanical components were produced using a rapid prototyping methodology (laser sintering of polyamide). The proxy bronchoscope was designed and modeled to physically replicate the size and handle fit of a real, flexible fiberoptic bronchoscope. To reproduce the angulation-control knob, a 2-axis mini Joystick (Parrallax Inc, Rocklin, CA) was integrated into the device's handle. This records the upward and downward input movements that are virtually transmitted to the tip of the bronchoscope. When the bronchoscope is physically inserted into a specific opening in the robotic patient interface device, integrated laser sensors track the probe's inward, outward, and rotational movements. All output signals are transmitted to the software in real time through a Bluetooth 4.0 connection, thus enabling precise localization of the probe's movement displayed on a realistic, 3-dimensional, computer-generated airways model. Rechargeable batteries are integrated into both devices enabling the simulator to be used cable-free.

Computing System. An iPad Pro tablet with an ARM10 processor (Apple Inc, Cupertino, CA) was selected as the simulator's computing platform. This device simultaneously offered a high-resolution display screen, a processor powerful enough to run the software and ensure highly realistic movement simulation, and the capacity to link wirelessly (Bluetooth 4.0 technology) to the simulator's other components. Furthermore, its lightness, ultraportable design, widespread availability, and affordable price were considered suitable for the project.

Software

A complete, 3-dimensional VR model of the airways was specifically designed to include the nose, mouth, pharynx, larynx, and complete tracheobronchial tree down to the subsegmental bronchi (Figure 2). The 3-dimensional model was programmed using Maya3D modeling software (Autodesk, San Rafael, CA). A database of chest radiographic computed tomography images and bronchoscopic videotapes of real patients were used to build the simulation model. A senior cardiothoracic anesthesiologist and a senior pulmonology physician validated the entire virtual model for the accuracy of airway anatomy and realistic-looking mucosal texture. To increase realism, a haptic feedback system was integrated into the device to mimic collisions between the tip of the bronchoscope and the mucosa. Auditory feedback simulating pulse oximetry during bronchoscopy was also included. Different bronchoscopic starting options were provided for each scenario: entry via the nose or mouth, with the patient in a supine (as performed by an anesthesiologist in an operating theatre) or sitting (as performed by a pulmonologist) position (Figure 3). The simulation software was written using the Unity multiplatform game engine, version 4.7.2 (Unity Technologies, San Francisco, CA). Several learning styles were integrated into the software and, as options, can be displayed directly on the model during bronchoscopic navigation. For example, to facilitate their education about lung anatomy, trainees can navigate a tracheobronchial tree with its relevant anatomical structures or bronchial segments either unlabeled or labeled with their names or numerical classification. An optional navigational tool can also be displayed during the simulation, allowing a precise localization of the proxy bronchoscope inside the virtual tracheobronchial tree (Figure 4). The software continuously and automatically records data such as the duration of procedures, time needed to reach specific anatomical targets, number of bronchial segments inspected, and number of

Figure 2. Screenshots from the 3-dimensional virtual reality model of the airways.

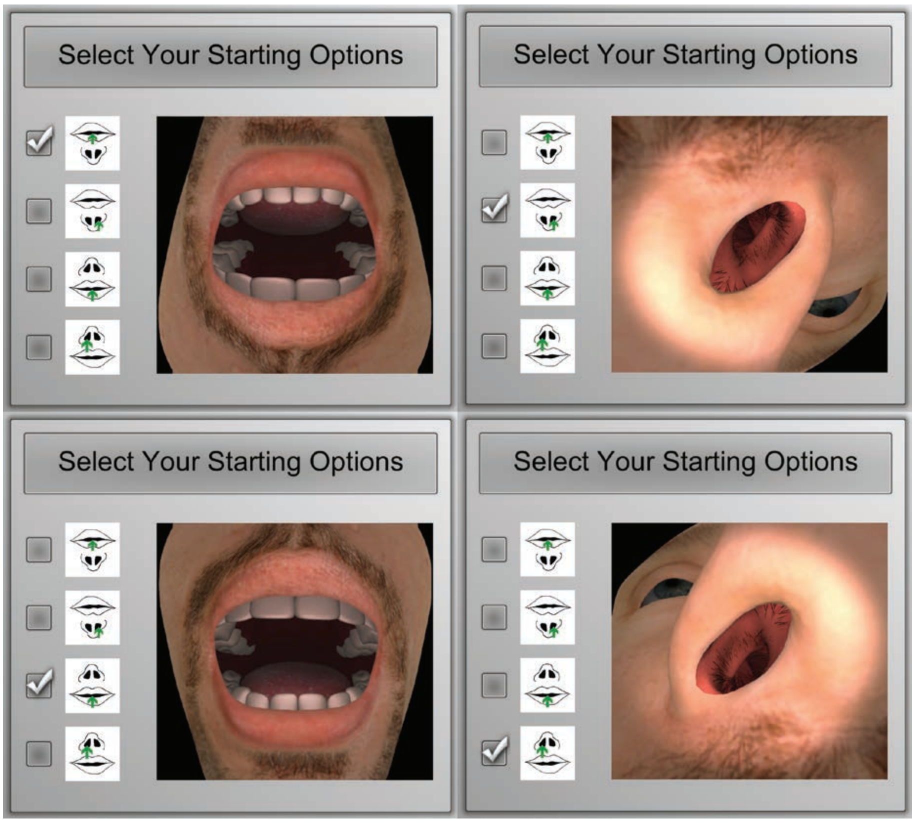

Figure 3. Computer Airway Simulation System software starting options (bronchoscopy via the mouth, via the nose, in supine or sitting position).

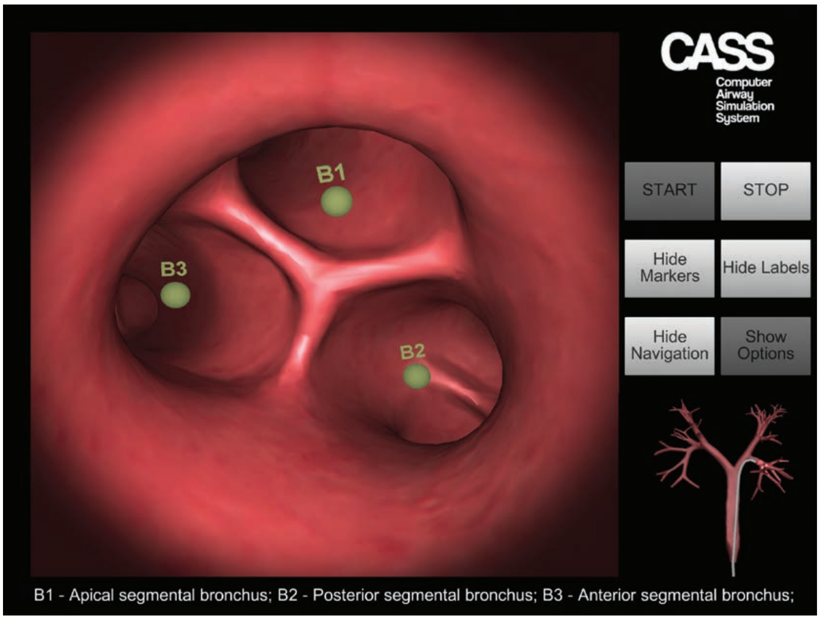

Figure 4. Teaching options: anatomical markers and labels, navigation roadmap tool. CASS indicates Computer Airway Simulation System.

bronchoscope-tip collisions against the tracheobronchial mucosa. These performance metrics are displayed at the end of the simulated investigation, giving the trainee immediate objective feedback (Figure 5). The results of each simulation session are recorded in a specific database and can be easily exported for documentary or research purposes.

Assessment of Face Validity

To gain some insight into the face validity of the CASS, Swiss board-certified anesthesiologists were asked to evaluate several aspects of the first fully functional simulator prototype. These volunteers were all attending a training session at a national difficult-airway management course (www.flava.ch), and they all received a short, standard introduction to using the simulator. Each participant was then given the opportunity to test the simulator independently for 30 minutes of self-training time; they had no previous experience with similar devices. After the training period, participants were asked to perform a simulated bronchoscopy, starting from the mouth and moving to the main carina. Procedure

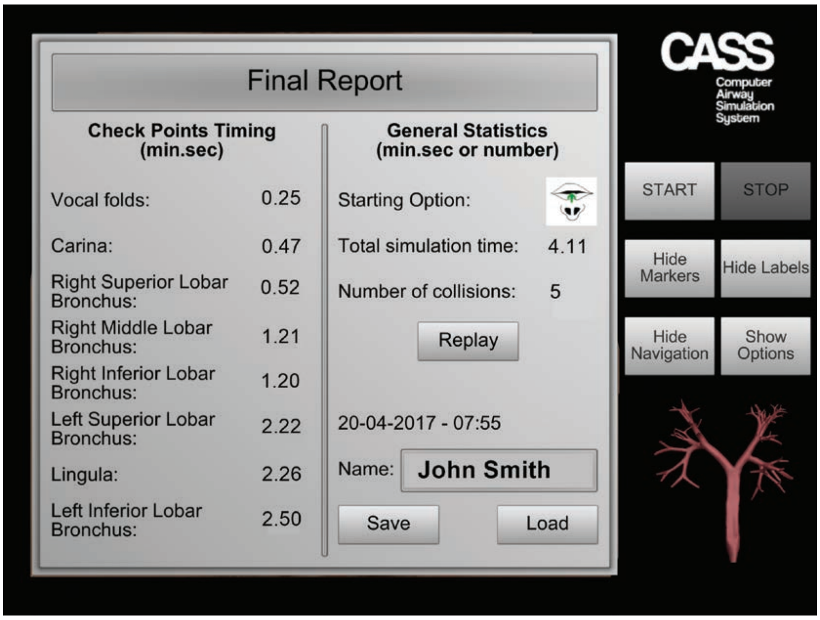

Figure 5. Screenshot of final report. CASS indicates Computer Airway Simulation System.

time was automatically measured in seconds. At the end of the session, participants answered a questionnaire asking them to rate several aspects of the simulator. The simulator's technical performance, realism, and adequateness for teaching were assessed using a 5-point Likert scale (1 = very poor, 2 = poor, 3 = acceptable, 4 = good, 5 = very good). Items related to technical performance inquired about the device's ease of use, how the bronchoscope proxy handled, and the system's reactivity. Reactivity was defined as how rapidly and fluidly the 3-dimensional airway model's screen image reacted in relation to the proxy bronchoscope's movements. Items related to realism inquired about anatomic accuracy and the graphical quality of the 3-dimensional airway model. Items related to adequateness for teaching included the simulator's usefulness for teaching and its educational value. Participants had the opportunity to add a written comment to each item to specify the reason for their rating.

The questionnaire's results were expressed using descriptive statistics (median [range] or mean [±SD]), as appropriate. Data were analyzed using the JMP 10 statistical package (SAS Institute Inc, Cary, NC).

RESULTS

Twenty-two Swiss board-certified anesthesiologists were enrolled, and every participant completed the assessment questionnaire fully after the simulation session. A majority (77.3%, 17/22) had >10 years of clinical experience, and 59.1% (13/22) of participants had performed >50 bronchoscopies during their medical practice. None of them had previous experience with VR bronchoscopy simulators. At the end of the self-training period, all the participants were able to perform a simulated bronchoscopy moving from the mouth (incisor teeth) to the carina. The median (range) procedural time was 66 seconds (30–96).

Technical performance was assessed positively, especially regarding "ease of use" and "bronchoscope proxy handling" (Table). System reactivity was assessed as satisfactory but improvable. Criticisms were related to the excessive reactivity of the upward and downward bronchoscope-tip motion transmission to the software, which increased handling difficulties during bronchoscopy. Many participants wrote comments about the simulator's interface, which they considered very intuitive and user-friendly.

Table. Survey Results From Virtual Reality Bronchoscopy Simulator Assessment Participants (n = 22)

Domain, Item	Rating (Mean ± Standard Deviation)
Technical performance	
Ease of use	4.3 ± 0.8
Bronchoscope proxy handling	4.0 ± 0.7
System reactivity	3.6 ± 1.1
Airway model realism	
Anatomical accuracy	4.5 ± 0.6
Graphical quality	4.7 ± 0.5
Adequateness	
Usefulness for teaching	4.9 ± 0.3
Educational value	4.8 ± 0.4

Likert-scale range: 1 = very poor, 2 = poor, 3 = acceptable, 4 = good, 5 = very good.

The accuracy of the anatomy of the airway model and the quality of the graphics were assessed as excellent (Table). Additional comments related to the accuracy of the 3-dimensional bronchial segmentation and realistic-looking texture of the tracheobronchial mucosa.

The simulator's usefulness for teaching and its educational value were also unanimously praised (Table). All the participants were enthusiastic about the teaching options included in the software and the simulator's high educational value in bronchoscopy training and the assessment of trainees.

DISCUSSION

This technical report describes the design and development of the CASS, which is, to the best of our knowledge, the first affordable, ultraportable VR bronchoscopy simulator. We also report on preliminary results supporting its face validity.

To fulfill the prototype device's predetermined criteria of affordability, ease of use, transportability, and adequate computing power, we selected an iPad-based engineering solution around which to develop our simulator. The proxy bronchoscope and robotic patient interface were created using a rapid prototyping methodology and simple electronic components already available on the market. A fully functional solution was developed within 24 months thanks to the financial support of 2 not-for-profit foundations promoting innovative research. The estimated overall cost of production of the final prototype's hardware was USD 2800, not including the cost of the iPad. Three-dimensional printing of mechanical components and the purchase of off-the-shelf electronics represented 60% of overall hardware costs; the remaining 40% involved assembly, calibration, and quality control. The final product is not yet ready for commercialization, and its final market price is currently difficult to estimate. Industrial manufacturing will substantially decrease the costs of hardware production; however, marketing and distribution costs will definitely increase the final price. Nevertheless, we are convinced that the CASS will be a far more affordable VR bronchoscopy simulation solution than other existing simulators.

Several Swiss board-certified anesthesiologists were able to evaluate the face validity of the CASS during this study. Based on their evaluations, the realism of the airway model (anatomical accuracy and graphical quality of the virtual airways) can be considered excellent. The simulator's technical performance as well as its hardware and software were considered intuitive and easy to use. The bronchoscope proxy's overall handling was assessed as good, providing participants with realistic feelings. Some concerns were expressed about the system's excessive or unrealistic reactivity, especially the upward and downward motion of the bronchoscope's tip. Future calibration and software improvements should easily correct this shortcoming. Despite the issue of oversensitivity, the simulator's overall bronchoscopic performance was judged sufficiently good and roughly comparable to a real bronchoscope. Furthermore, the median time needed to perform a simulated bronchoscopy from the mouth to the carina was 66 seconds, which is similar to the procedural time reported in fiberoptic intubation studies performed on live patients.[21–23]

All the participants pointed out the high educational value of teaching bronchoscopy using the CASS's VR interface. They were enthusiastic about both the self-teaching possibilities integral to the CASS and the objective performance assessment options included in the software. Overall, these results clearly support the face validity of the task the CASS was supposed to model, that is, bronchoscopy. Despite the undeniable interest in simulation-based medical education and its capacity to offer repeated effective training opportunities with no ethical or safety issues for patients, VR bronchoscopy simulators are as yet limited in distribution. Their high costs have perhaps limited their spread to dedicated training centers. Even in a high-income country like Switzerland, none of the participants in the national airway course mentioned above had ever had the chance to train on existing simulators. Smartphones and tablets are now widely available, and the potential for teaching via medical simulation apps has already caught the interest of younger generations of physicians and medical students. To the best of our knowledge, the CASS is the first VR bronchoscopy simulator to run on a tablet platform. We believe that this modern VR medical simulator could prove attractive and interesting to medical trainees, and its use could become widespread thanks to its relatively affordable purchasing price. Our VR simulator was specifically designed to teach the hand–eye coordination needed to place a fiberscope into the trachea and to examine the airways of a normal patient. Future developments include adding simulated anatomical pathologies and scenarios involving difficult case studies.

LIMITATIONS

Only 22 anesthesiologists were enrolled in this preliminary validation study, which could have led to a selection bias as no medical professionals from other specialities performing pulmonary and airway endoscopy (such as chest physicians or ear, nose, and throat specialists) were included. The investigators aimed to use this pilot study to evaluate the model's overall face validity by collecting participants' subjective assessments of a time-limited self-training session. The final objective assessment of participants' performance was limited to 1 timed simulated bronchoscopy from mouth to carina. However, the lack of a baseline evaluation limits the interpretation of these results, and future studies should aim to assess the effects of repeated practice on the simulator. Similarly, although demonstrating the model's face validity is an important step in the overall validation of a virtual simulator, it does not guarantee its training efficacy. Therefore, the CASS's true educational value and potential clinical impact as a new VR simulator for bronchoscopy will require further studies involving physicians training on it, particularly novice bronchoscope users. Sequential evaluations of skills acquisition and improvements in technique should be measured using validated objective metrics.[24,25] Finally, because the participants were not familiar with the other existing VR bronchoscopy simulators, they may have been more forgiving of the CASS's weaknesses.

CONCLUSIONS

This technical report details the design and development phases of the CASS, a prototype VR bronchoscopy simulator. It also reports on preliminary results which evaluate the simulator and support its face validity. Subjective assessments of the CASS by anesthesiologists were excellent, especially as a tool for teaching and with regards to the model's anatomical accuracy and graphical quality. In the system's next version, reactivity will be refined to improve the sensitivity of its handling during simulated bronchoscopy.

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DISCLOSURES

Name: Gabriele Casso, MD.
Contribution: This author helped conceive the study idea; design, supervise, and conduct the study; collect and analyze the data; and write and revise the article.
Conflicts of Interest: G. Casso is a member of the Board of the FLAVA Foundation.

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Contribution: This author helped design and conduct the study, collect and analyze the data, and write and revise the article.
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Conflicts of Interest: None.
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Contribution: This author helped design the study, analyze the data, and revise the article.
Conflicts of Interest: None.
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