CHEST

Virtual Reality Anatomy Trainer Turns Teaching Endobronchial Ultrasound Inside-Out

Melissa L. New, MD; Tristan J. Huie, MD; Dru Claar, MD; Timothy Amass, MD; Ryan A. Peterson, PhD; Max McGrath, MS; Nicholas Jacobson, MDes; Anna Neumeier, MD; and Darlene Nelson, MD

BACKGROUND: Traditional approaches for learning anatomy for curvilinear endobronchial ultrasound (EBUS) require learners to mentally visualize structures relative to the position of the bronchoscope. Virtual reality (VR) can show anatomy from the perspective of bronchoscopic tools.

RESEARCH QUESTION: Does the use of a VR anatomy trainer for teaching EBUS-associated anatomy improve procedural performance compared with traditional methods?

STUDY DESIGN AND METHODS: In this randomized, crossover study design, participants studied EBUS-related anatomy during 2 sequential sessions using a VR trainer and a traditional modality (2-dimensional pictures or a 3-dimensional model). An EBUS simulator was used to test performance at baseline and following each training session. User experience and preferences were evaluated by using a mixed-methods approach of surveys and interviews. Spatial reasoning ability was measured by using the Mental Rotation Test.

RESULTS: Sixty-eight fellows and residents at 3 institutions completed the study. All 3 learning methods improved EBUS performance significantly following the first, but not second, learning session. Learners spent more time (1.37 minutes) with VR, but no training method produced a greater improvement. Spatial reasoning ability was associated with improved EBUS performance. This impact was modified by training method: the VR approach leveled the impact of baseline spatial reasoning. The VR approach was preferred by 96% of learners. Qualitative data revealed a positive VR user experience with focused anatomy learning, ease of use, acceptable realism, and tolerance. This novel "inside-looking-out" perspective helped learners understand anatomy from the vantage of procedural tools and to create a mental map, but interpreting ultrasound remained challenging.

INTERPRETATION: A VR anatomy trainer was preferred by learners because it provided visualization that aligned best with the procedural perspective. This approach helped learners of all spatial reasoning ability improve their procedural performance.

CHEST 2025; 167(5):1440-1450

KEY WORDS: anatomy; bronchoscopy; extended reality; medical education; spatial reasoning; virtual reality

ABBREVIATIONS: 2D = 2-dimensional; 3D = 3-dimensional; EBUS = endobronchial ultrasound; EBUS-STAT = Endobronchial Ultrasound Skills and Tasks Assessment Tool; MRT = Mental Rotation Test; VR = virtual reality

AFFILIATIONS: From the Department of Medicine, Division of Pulmonary Sciences and Critical Care Medicine (M. L. N., T. J. H., T. A., and A. N.), University of Colorado; Rocky Mountain Regional VA Medical Center (M. L. N.), Aurora; National Jewish Health (T. J. H.), Denver, CO; Department of Medicine (D. C.), Division of Pulmonary and Critical Care Medicine, University of Michigan, Ann Arbor, MI; Denver Health Medical Center (T. A. and A. N.), Denver; Department of Biostatistics & Informatics (R. A. P. and M. M.), University of Colorado, Colorado School of Public Health, Aurora; Tangible Industries (N. J.), Denver, CO; and the Department of Medicine (D. N.), Division of Pulmonary and Critical Care Medicine, Mayo Clinic, Rochester, MN.

CORRESPONDENCE TO: Melissa L. New, MD; email: Melissa.New@cuanschutz.edu

DOI: https://doi.org/10.1016/j.chest.2024.11.032

Take-Home Points

Study Question: Does the use of a virtual reality (VR) anatomy trainer depicting endobronchial ultrasound (EBUS)-associated anatomy from the perspective of being inside the airway improve procedural performance compared with traditional methods of 2-dimensional images or a 3-dimensional model?

Results: With participation of 68 fellows and residents at 3 institutions, results showed that although average EBUS performance improved with all learning approaches, VR was the preferred modality by 96%, and it was the only approach with improvement in EBUS performance independent of spatial reasoning skill.

Interpretation: A VR trainer that provided EBUS anatomy visualization aligned with the procedural perspective helped learners improve their performance regardless of spatial reasoning ability.

Anatomy learning is a critical component of procedural education. Traditional teaching approaches have used an "outside-looking-in" perspective with diagrams, models, and cadaveric dissection. This perspective translates naturally to surgical procedures in which an operator uses an outside-looking-in perspective with their own eyes and tools entering from outside the body.

Developments in bronchoscopy have advanced our ability to diagnose respiratory disease.[1,2] Endoscopic procedures require a different approach to anatomy, with the proceduralist viewing structures from the perspective of their instrument; that is, from the "inside looking out." For learners using 2-dimensional (2D) and 3-dimensional (3D) learning materials, this requires them to mentally rotate anatomic structures to visualize their location from the perspective of their scope.

Endobronchial ultrasound (EBUS) is a bronchoscopic method to visualize and guide sampling of airway-adjacent lymph nodes and lesions. Mediastinal lymph node stations have boundaries that are determined by vascular structures. This requires an EBUS operator to correctly recognize vascular structures to then identify a lymph node station and apply the appropriate lung cancer stage to a patient. Anatomic understanding and correct landmark identification are thus crucial components for procedural competence but ones that are challenging to learn.[3,4]

Virtual reality (VR) is a promising approach for anatomy instruction with demonstrated benefits for learners related to the presentation of 3D spatial relationships with stereoscopic vision and interactive learning.[5-9] With broad capability in the way visual information is portrayed, VR can provide a novel perspective on anatomy for endoscopic procedures. We developed a VR anatomy trainer that allows users to see anatomic structures from the perspective of being inside the airway. The goal of the current study was to assess the impact of teaching EBUS-related anatomy using this "inside-looking-out" perspective compared with traditional approaches.

Study Design and Methods

Participants

Pulmonary and critical care medicine fellows and internal medicine residents at Mayo Clinic Rochester, University of Colorado, and University of Michigan were eligible to participate. They were recruited through email, word of mouth, and fellowship educational activities. Participation was voluntary and did not affect evaluation.

The study was approved or deemed exempt by each participating institution's institutional review board.

Learning Materials

The VR anatomy trainer was developed in collaboration with the Inworks Innovation Initiative at the University of Colorado. A digital model of the airway tree was created from a de-identified patient CT scan and combined with digitally drawn vascular structures (Fig 1). Accuracy of the size and location of the anatomic structures were confirmed by reference to de-identified patient scans, anatomy textbooks, radiology literature, and experts in EBUS. The VR trainer places the user inside the airway with full visual degrees of freedom and ability to navigate from the vocal cords to the lobar bronchi using a VR controller. A controller button toggled the appearance of the airway walls from opaque to translucent, revealing vascular structures and lymph node stations that were labeled and colored in familiar convention (Fig 1A, Video 1). The VR anatomy trainer was used on Oculus Quest 2 headsets (Meta Platforms Inc).

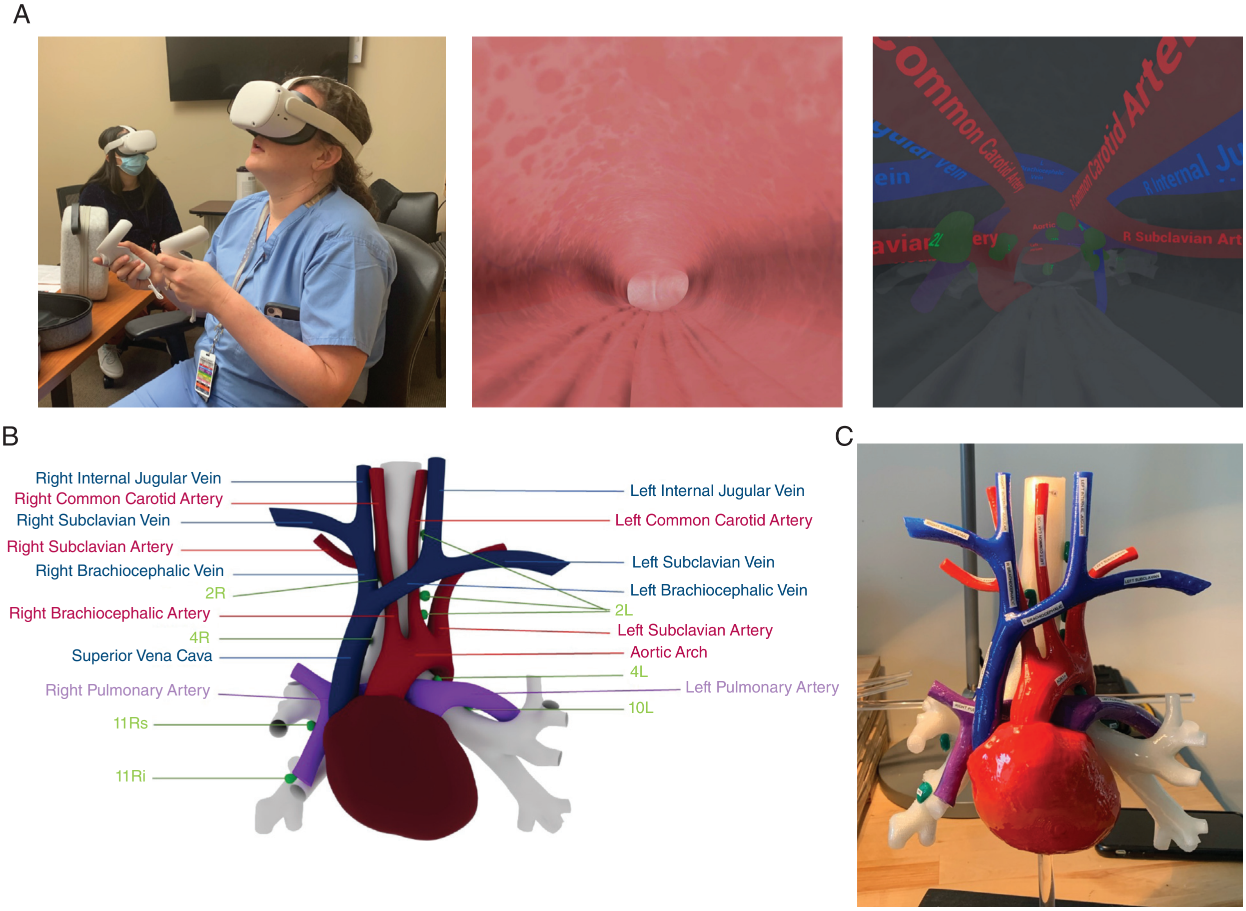

Figure 1 – *A-C, Study materials. A, The virtual reality simulator in use by study participants (left) with a representative view of the program in the airway view (center) and translucent view (right). Two-dimensional images (B) and a 3-dimensional model (C) were produced using the same digital model as was used for the virtual reality program.*

The digital anatomic model developed for the VR program was used to produce anatomy learning materials for 2D and 3D learning approaches. The 2D materials were printed labeled images from anterior, posterior, right and left orientations (Fig 1B). A 3D model generated by a 3D printer had structure labels applied (Fig 1C).

Study Procedure

This study used a randomized, crossover design and a mixed-methods approach to explore the impact of training materials on anatomy learning (Fig 2). Participants completed a pre-session survey about demographic characteristics, prior EBUS experience, self-assessed spatial learning ability, and anticipated learning modality preference. Self-assessed knowledge and confidence in ability to identify vasculature and nodal stations were assessed (5-point Likert scale; 1 = strongly disagree; 5 = strongly agree). To objectively assess participant spatial reasoning skills, we used the validated redrawn Vandenberg and Kuse Mental Rotation Test (MRT), which has been associated with anatomy learning and procedural performance.[10-12] The MRT was administered according to published recommendations and scored from 0 to 24, with higher scores indicating better spatial reasoning ability.[13]

EBUS anatomy performance was assessed at baseline (Pre-Test), after which participants were randomly assigned in a 1:1:1 fashion to one anatomy learning modality for the first learning session (Learning 1): 2D, 3D, or VR. Lymph node station anatomic boundaries were provided. Learning was self-paced, and time spent in Learning 1 was recorded. Following Learning 1, participants completed Post-Test 1 of EBUS anatomy performance. Those randomized to the 2D or 3D modality for Learning 1 then used VR for Learning 2; those initially randomized to VR were randomly assigned the 2D or 3D method for Learning 2. The procedures for Learning 1 and Post-Test 1 were repeated for Learning 2 and Post-Test 2, respectively.

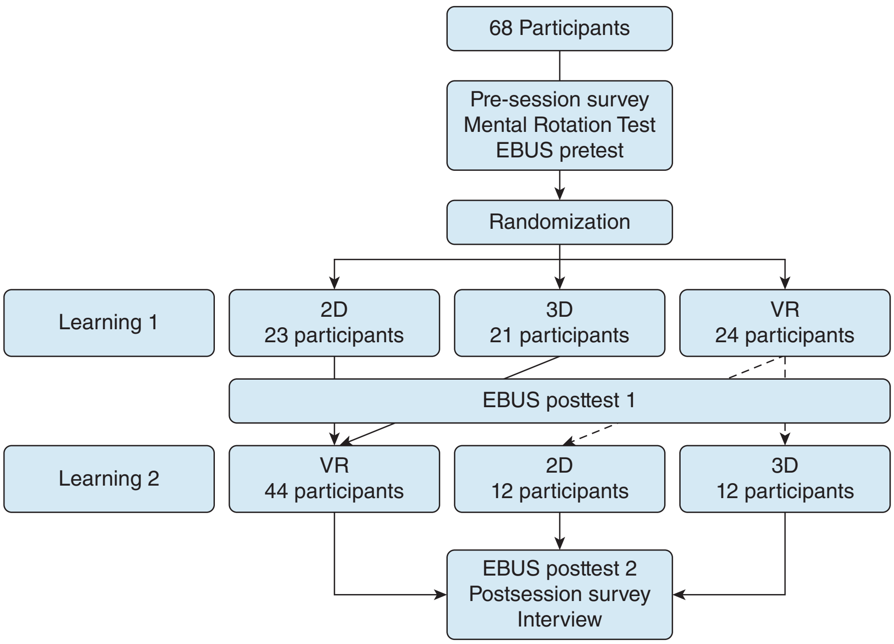

Figure 2 – *Study design. Flow of participants through the randomized, cross-over study protocol. EBUS pretest and each posttest were performed on the Simbionix BRONCH Mentor, using 2 anatomy-focused items from the validated Endobronchial Ultrasound Skills and Tasks Assessment Tool. 2D = 2-dimensional; 3D = 3-dimensional; EBUS = endobronchial ultrasound; VR = virtual reality.*

EBUS anatomy performance was assessed using questions from the validated Endobronchial Ultrasound Skills and Tasks Assessment Tool (EBUS-STAT) pertaining to anatomy identification (items 4 and 5).[14] Participants' identification of anatomic structures was scored according to the EBUS-STAT convention; time to identification was recorded for correctly identified structures. There was a maximum 35 points available: 15 for lymph node anatomy (5 points per station, 3 assessed) and 20 for vascular anatomy (4 points per structure, 5 assessed). The assessment was performed by using the Simbionix BRONCH Mentor (Surgical Science), EBUS Case 6.

Following Post-Test 2, participants completed a postsession survey with the same self-assessment questions, plus questions about learning modalities. The postsession survey was followed by an interview about their VR anatomy trainer learning experience (e-Appendix 1).

Data Analysis

Primary analyses consisted of a mixed model with subject-level random intercepts and post-training score as the outcome. The fixed effects included most recent training method (our primary explanatory variable), time point (Post 1 vs Post 2), and pre-training score (centered about its sample mean). The effect of interest was measured as the expected change in EBUS score for VR compared with the 2D or 3D method, controlling for pre-score and time point. We used this model's intercept to estimate the predicted score following each learning method for a participant with a mean pre-training score. We then investigated secondary research questions by adding additional fixed effects to explore whether level of training (resident vs fellow), number of procedures, time point, or mental rotation capacity modified the effect of the learning modality. For MRT, Akaike information criterion was used to guide a simplification of the model parameterization wherein groups were compared prior to and following VR training rather than by most recent training method.

To assess the impact of learning modality on time to provision of correct response, a similar mixed model was estimated with the (logged) time to provision of correct response as the outcome and additional fixed effects accounting for pretraining response times and assessment type (vascular vs lymph nodes). A mixed-model of time spent in learning modality with random intercepts and a fixed-effect for learning modality assessed whether participants spent more time in VR compared with the 2D or 3D modality.

The change in knowledge and confidence scores that occurred between learning periods was evaluated by using Wilcoxon signed-rank test. The relationship of item-specific confidence and perceived knowledge to actual item-level learning was assessed by using 6 mixed models with subject-level random intercepts, one for each combination of assessment type and measure of confidence and perceived knowledge. Each model includes pretraining score and a measure of confidence or perceived knowledge level as predictors. Pairwise McNemar tests were used to compare learning modality preferences prior to and following assessment, and to compare these preferences with each individual's stated "best" modality.

To assess the qualitative experience of the training modalities, all individuals participated in a recorded semi-structured in-person interview. These were conducted by 1 of 3 researchers and were tailored to evaluate the user learning experience. These were transcribed and all identifying information removed. A preliminary codebook was created by 2 authors (T. A. and M. L. N.) who independently identified emerging concepts and codes. Saturation of codes was achieved after reviewing 15% of the transcripts. Each transcript was independently analyzed by the same 2 authors (T. A. and M. L. N.), who then met to discuss and resolve any coding discrepancies. These codes were then analyzed using the qualitative software NVivo 14 (QSR International) to develop themes and subthemes.

Because no formal sample size justification was performed, we produced 95% profile likelihood CIs for all reported model-based estimates and acknowledge that tests for effect moderation may suffer from low power.

Results

Between October 2022 and September 2023, a total of 68 participants enrolled in the study; 44 (65%) were randomized to the 2D or 3D learning then VR, and 24 (35%) were randomized to undergo VR then 2D or 3D learning. Learners had a median age of 32 years (interquartile range, 2 years), and 37 (54%) identified as female. Fifty-three (78%) learners were fellows, and 15 (22%) were residents. Eighteen (34%) fellows were in their first year of fellowship (Table 1). Prior to the

TABLE 1] Participant Characteristics for All Individuals and Broken Down According to Study Group

Characteristic	Overall (N = 68)	2D → VR (n = 23)	3D → VR (n = 21)	VR → 2D (n = 12)	VR → 3D (n = 12)
Demographic variables					
Age, y	32.0 (2.0)	32.0 (2.0)	32.0 (2.0)	31.0 (2.8)	31.0 (3.0)
Self-identified sex					
Female	37 (54%)	15 (65%)	11 (52%)	4 (33%)	7 (58%)
Male	31 (46%)	8 (35%)	10 (48%)	8 (67%)	5 (42%)
Experience level					
What level of training are you?					
Fellow	53 (78%)	20 (87%)	16 (76%)	9 (75%)	8 (67%)
Resident	15 (22%)	3 (13%)	5 (24%)	3 (25%)	4 (33%)
Fellow year					
1st year	18 (41%)	8 (44%)	4 (36%)	3 (38%)	3 (43%)
2nd year	12 (27%)	4 (22%)	3 (27%)	4 (50%)	1 (14%)
3rd year	13 (30%)	6 (33%)	3 (27%)	1 (12%)	3 (43%)
4th year	1 (2.3%)	0 (0%)	1 (9.1%)	0 (0%)	0 (0%)
Approximate No. of EBUS procedures I have participated in:					
0	23 (34%)	5 (22%)	8 (38%)	4 (33%)	6 (50%)
1-5	16 (24%)	8 (35%)	5 (24%)	2 (17%)	1 (8.3%)
6-10	11 (16%)	5 (22%)	2 (9.5%)	3 (25%)	1 (8.3%)
11-15	7 (10%)	0 (0%)	2 (9.5%)	3 (25%)	2 (17%)
16-25	5 (7.4%)	3 (13%)	2 (9.5%)	0 (0%)	0 (0%)
> 25	6 (8.8%)	2 (8.7%)	2 (9.5%)	0 (0%)	2 (17%)
Scores					
Mental Rotation Test score	9.5 (5.0)	11.0 (7.0)	8.0 (4.0)	9.5 (4.0)	12.0 (4.5)
Pre-learning score	14.0 (18.0)	18.0 (16.5)	12.0 (17.0)	16.0 (24.0)	12.0 (11.0)

Data are presented as median (interquartile range) unless otherwise indicated. EBUS = endobronchial ultrasound.

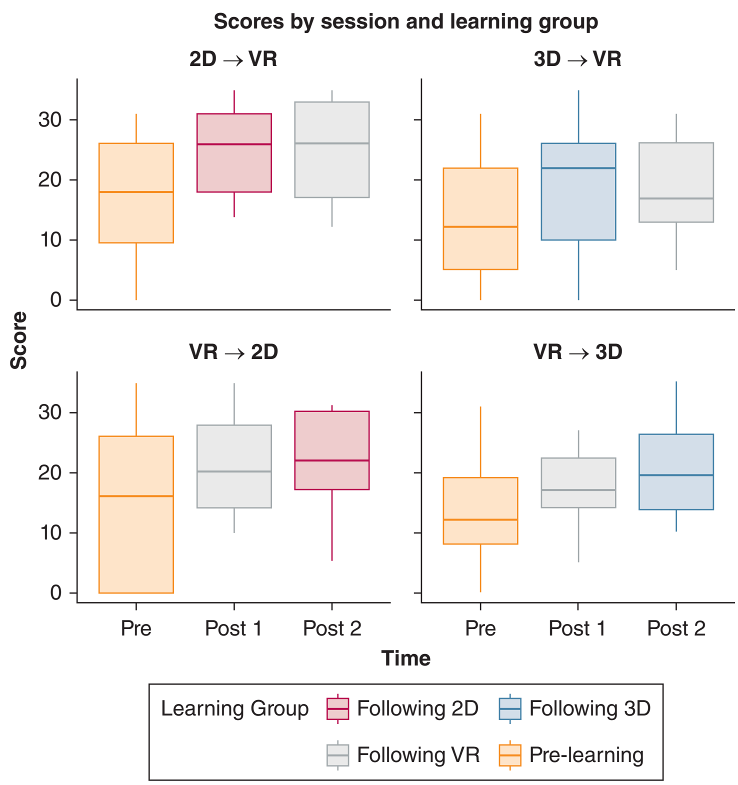

Figure 3 – *Scores according to session and learning group. Box and whisker plots for participant scores broken down by learning group: 2D to VR (23 participants), 3D to VR (21), VR to 2D (12), and VR to 3D (12). All 3 learning methods (2D, 3D, and VR) showed significantly higher EBUS-STAT scores following the first learning session. Learning with either modality produced a similar improvement in scores, although scores remained flat at the second post-assessment. 2D = 2-dimensional; 3D = 3-dimensional; EBUS = endobronchial ultrasound; VR = virtual reality.*

study, 23 (34%) learners had no experience with EBUS, whereas 29 (43%) had participated in at least 6 EBUS procedures. Learners scored a median of 14 (interquartile range, 18) on the pre-session EBUS assessment and had a median MRT score of 9.5 (interquartile range, 5).

Prior to the learning session, 19 (28%) participants agreed with the sentiment "I know how to identify mediastinal vascular structures using EBUS," and 27 (40%) agreed with the statement "I know how to identify mediastinal lymph node stations using EBUS." Following the session, 53 (78%) and 56 (82%) learners agreed with those statements, respectively (e-Table 1). Self-assessed improvement in knowledge and confidence was statistically significant for each question ($P <$ .0001). Prior to being exposed to any learning methods, 45 (66%) said they would prefer to learn via VR. After being exposed to both VR and non-VR learning methods, 64 (96%) learners said they preferred learning via VR, and 64 (96%) stated a preference to use VR for learning anatomy for other types of procedures.

All three learning methods (2D, 3D, and VR) produced higher EBUS-STAT scores following the first learning session (Fig 3). The results from the primary mixed model indicated that adjusted for pre-score and time point, there was no evidence of a difference between learning methods (a mean difference of –1.0 point; 95% CI, –3.03 to 0.97; $P = .32$). However, both learning methods saw significantly improved outcomes following learning; for someone with an average pre-score of 14.6, the expected score following the first 2D/3D learning session was 21.6 points (95% CI, 19.7 to 23.4), and 20.6 points after the first VR learning session (95% CI, 18.4 to 22.8).

The MRT score was highly associated with EBUS scores, but this effect was significantly modified by training method. Specifically, adjusting for pre-score and learning session, for individuals who had yet to receive VR training (ie, had only received 2D or 3D training), each additional point in the MRT score was associated with a 0.88-point increase in post-training EBUS score (95% CI, 0.49 to 1.28). This association was significantly reduced by 0.59 (95% CI, –1.04 to –0.16) following VR training, after which the association became 0.29 and was no longer significant (95% CI, –0.06 to 0.64) (Fig 4).

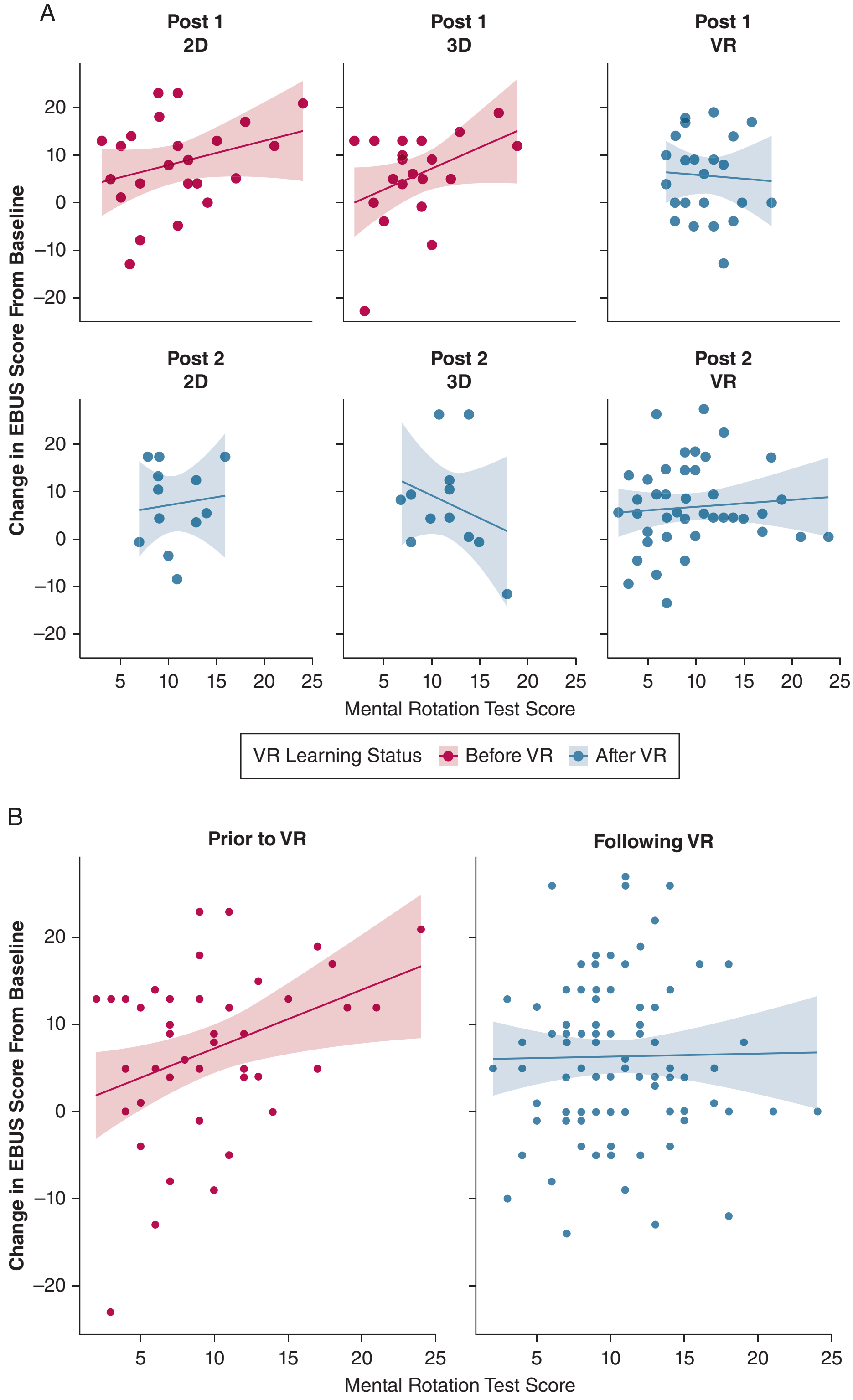

Figure 4 – *A, B, Impact of MRT score on change in EBUS performance. Graphical representations of statistical modeling of the impact of the MRT score on change in EBUS performance. A, Change in EBUS from baseline according to MRT score for each study group. B, Groups combined into those who have only used 2D or 3D learning approaches (Prior to VR) and those who have used the VR learning approach (following VR). MRT score was highly associated with EBUS scores, but this effect was significantly modified by training method. Specifically, the MRT score significantly predicted EBUS score improvement in the "Prior to VR" group, but this effect was significantly mitigated in the "Following VR" group. 2D = 2-dimensional; 3D = 3-dimensional; EBUS = endobronchial ultrasound; MRT = Mental Rotation Test.*

TABLE 2] Qualitative Themes That Emerged From Qualitative Analysis, With Representative Quotations

Theme	Quote
VR trainer user experience	"It felt pretty, pretty normal. I had really never used any VR device before, and within a minute or so it was pretty easy to pick up and use."
	"I thought it was very realistic. And it felt like I was actually seeing what I saw on the screen of the bronchoscope. But then plus . . . it was seeing through the walls, which was nice."
	"There was a little bit of like motion sickness almost with it for prolonged use, but maybe I was in there for longer than I should have been, just kind of playing around."
	"Honestly, I really struggle learning anatomy and I have through all of my training, and I am shocked at how quickly that worked for me. So I would say I think positively of the virtual reality."
Learning with bronchoscopic perspective	"I mean, that's the perspective you always see anyway. So it's kind of intuitive. It was more intuitive than the 3D model, because you're looking from the inside out as opposed to the outside in."
	"I think it just helps me when I'm actually doing real EBUS to recognize the structures because I have difficulties translating the pictures to a 3D structure when I'm in the structure."
	"So what I found to be really helpful was the fact that the virtual reality was still combined with a 3D anatomical model. And I thought that those together were extremely helpful in helping me to visualize and review the anatomy. So I felt like that going into this after using that I had a much clearer understanding of what I could expect in the EBUS trainer."
	"Especially for the vessels, it kind of gives you a better sense of trajectory and how they wrap around, especially than, like, a 2D model, but even a 3D model, it's harder to get a sense of that. It was kind of nice making us kind of look around and see where it's going from a position in the airway."
Creation of mental map for procedural application	"It did help with my intrinsic visualization . . . when I was doing the bronch, I was essentially picturing what I had seen in the virtual reality."
	"I think it translates well, because you kind of create that mental image in the VR world, and then as you kind of scan up and down things, you can overlay what you're seeing onto your mental image."
Additional challenge of the ultrasound view	"When I went to do it on EBUS, I still found myself struggling a little bit, because I would try to remember the mental image that I had that was like 3D and it was fermented in my head, and then it's like EBUS is its own step further."
	"The only thing that is a little difficult is . . . the virtual reality still has a pretty anatomy view, if there's any way to have another layer that tried to mimic the ultrasound view, that would be really helpful."
Educational implementation of VR anatomy trainer	"I think it would be extraordinarily helpful early on in training. Because it just gives you a better roadmap than any PowerPoint slide might give you, which was kind of what… I was able to use when I was in the early part of my fellowship."
	"If I had had this at the beginning of fellowship, I would have had a lot more confidence going into the bronchoscopy suite, and then I could have focused on things like . . . the actual hand-eye coordination skills, understanding how the bronchoscope moves, and there would have been a great deal more comfort with that."
	"I think this is great as a preprocedural review, to give you a roadmap for how am I going to approach these structures, so that way you can go in and you can have some sort of visualized plan of where I'm going to go to locate these things, instead of going in blind, so to speak."

3D = 3-dimensional; EBUS = endobronchial ultrasound; VR = virtual reality.

We found no evidence of learning method effect modification according to time point ($P = .55$), number of EBUS experiences ($P = .54$), or learner level ($P = .29$). We also found no significant associations between learning modality and time to provision of correct response ($P = .49$). VR learning was associated with 1.37

minutes longer time spent training (95% CI, 0.06-2.67), compared with 2D or 3D training (average, 8.02 minutes; 95% CI, 7.0-9.1).

Adjusting for pre-score, we found that learners who responded positively regarding their post-learning confidence in their ability to identify vascular structures had a 3.01 higher vascular score (95% CI, 0.64-5.38) than those who responded neutrally, on average. Similarly, those who responded positively regarding their post-learning knowledge of vascular structures had a 3.42 higher vascular score than those who responded neutrally (95% CI, 0.22-6.63). We found no evidence of an association between item-specific knowledge and confidence and change in lymph node scores.

Qualitative analysis of focused interviews revealed several themes: the experience of using the VR anatomy trainer; the impact of learning with the bronchoscopic perspective; creation of an anatomical "mental map"; the additional challenge of the ultrasound view; and recommendations for educational use (Table 2). In general, users reported a favorable experience with the VR trainer. They found it easy to use, even for those without prior VR experience; few participants reported motion sickness with using VR. Participants found the airway view to appear realistic: "It felt like I was actually seeing what I saw on the screen of the bronchoscope. But then, plus . . . it was seeing through the walls, which was nice."

The perspective of being inside the airway was often noted as the reason for the perceived benefit of and preference for the VR anatomy trainer. This vantage point "avoided having to rotate things in your mind, it was sort of already in the layout that you're used to." Users found this particularly beneficial regarding vascular anatomy, that the VR "gives you a better sense of trajectory and how they wrap around" and allowed users to create a mental map to apply to subsequent EBUS attempts. Some found the use of a combination of perspectives to be helpful, using a 3D model along with the VR trainer to provide a more comprehensive anatomic understanding. Many cited the additional challenge of using and interpreting ultrasound because "it's like EBUS is its own step further"; participants recommended inclusion of an ultrasound view in the VR trainer. The benefit of isolating anatomy learning from other procedural skills was noted: "If you did separate those 2 things, then you would be able to teach the procedural skill potentially a little bit easier if people weren't focusing on learning multiple things at once."

Discussion

VR and other forms of extended reality have a growing role in anatomy education.[5,8,9,15] Although VR and extended reality can take many forms, we are the first, to our knowledge, to create and test a VR program that provides procedural anatomy training from the perspective of bronchoscopic instruments, from the inside-looking-out. Our mixed methods data provide an in-depth understanding of the differences and benefits to using this novel approach to learn EBUS-relevant anatomy compared with traditional anatomy teaching methods. We found VR to be as effective as traditional methods, while possibly improving learning for those with poorer baseline spatial reasoning ability.

When learning with traditional outside-looking-in 2D and 3D approaches, the amount of procedural improvement learners demonstrated correlated with spatial reasoning: learners with higher spatial reasoning ability had greater improvement in procedural performance. The impact of spatial reasoning ability on EBUS improvement was mitigated when VR was used as a learning modality; the inside-looking-out perspective allowed equitable learning of anatomy irrespective of spatial reasoning ability. Our qualitative data complement this finding: many participants discussed the difficulty of mentally rotating structures to picture anatomy from another perspective and the benefit of the VR trainer to facilitate this. Others appreciated the integration of the outside-looking-in perspective with the inside-looking-out view to better understand the interaction of anatomic structures. These findings of varied anatomy learning preferences and differential benefits based on spatial reasoning ability raise the prospect of personalized education within procedural teaching.

From a learner perspective, there was an overwhelming preference for the VR anatomy trainer. Seeing anatomy from a procedural viewpoint was useful to many participants and was repeatedly cited as the reason for VR trainer preference. The VR trainer helped to create a "mental map," such that when doing a procedure, they could picture the location of vascular structures surrounding the airways, something they had been unable to accomplish with other learning methods. Our quantitative data showed that self-assessed vascular anatomy knowledge and confidence correlated with better vascular anatomy performance, which is perhaps related to learners having a better spatial sense with a "mental map" of the vascular structures.

EBUS is a complex procedure requiring the integration of multiple technical and cognitive skills. Teaching complex procedures can benefit from breaking them into discrete micro skills to minimize cognitive load.[16-18] Our study is consistent with this approach of focusing on micro skills: we saw improvement in procedural skill after dedicated anatomy teaching, despite a relatively short training duration of focused self-directed learning. The benefit of self-directed learning may have been limited, however, in the absence of expert guidance or performance feedback as we did not see significant improvement on the second post-test compared with the first.

Participants highlighted the benefit of focusing on learning anatomy independent of other procedural components but raised an additional challenge in applying anatomy learning to procedural performance: ultrasound image interpretation. Unprompted, participants repeatedly brought this up as a challenge, as well as a potential way to improve the VR anatomy trainer learning experience. Although we deliberately focused on learner interaction with anatomy teaching methods and chose not to incorporate ultrasound teaching into the current study, an interactive ultrasound view is a feasible addition to the VR anatomy trainer.

Increased accessibility and portability are a benefit of VR. Our participants reported they would use VR anatomy training prior to clinical bronchoscopy experiences, such as "just-in-time" retraining. We intentionally developed our VR program to be compatible with the Oculus headset, which does not require a computer for use and has a lower price relative to other VR headsets, as cost is an important barrier to educational material dissemination.

The current study has numerous strengths, including being a multisite study with a sample size comparable to or exceeding previous bronchoscopy educational studies.[3,19] Our decision to enroll trainees interested in bronchoscopy further increases relevance and generalizability. Our assessment of spatial ability used a validated tool with relevance to anatomy learning and the specific task required to apply anatomy learning to procedural performance. In addition to subjective outcomes, the validated EBUS-STAT tool was used for objective assessment. The mixed-methods approach provides a comprehensive and rich exploration of this novel anatomy trainer.

One limitation is that outcomes were of EBUS performance on a simulator, not patient-level outcomes. However, the EBUS-STAT can be used in the simulation setting, as in prior EBUS educational studies.[3,14,20] The current study outcomes were assessed immediately following training, and thus long-term impact on skill retention remains uncertain. In addition, we chose to simply provide learning materials rather than to direct a learning or procedural method. This differs from an EBUS educational approach used by some, a stepwise sequence of specific ultrasound views.[21] Differences between these approaches to teaching procedural anatomy have not been explored and can be the subject of future work. Comprehensive EBUS skill assessment includes elements beyond anatomy, including bronchoscope manipulation and transbronchial needle aspiration, among other skills; these were not included in the current anatomy-focused study, although they are important clinically. Some of our tests for effect modification were limited by low subgroup sample size; additional research would be beneficial to validate our results.

Interpretation

Dedicated EBUS-related procedural anatomy teaching improved the ability of learners to correctly identify anatomic structures. Use of a VR anatomy trainer provided an inside-looking-out view that was preferred by learners given its alignment with the procedural perspective. Although benefit from traditional anatomy learning methods correlated with spatial reasoning skill, this novel approach helped learners of all spatial reasoning abilities to improve their procedural performance.

Funding/Support

This work was supported by funding from the University of Colorado Department of Medicine Program for Academic Clinician Educators.

Financial/Nonfinancial Disclosures

None declared.

Acknowledgments

Author contributions: M. L. N. takes responsibility for the content of the manuscript, including integrity of the data and accuracy of the data analysis. M. L. N., D. N., D. C., T. J. H., N. J., A. N., and T. A. contributed substantially to the study design; M. L. N., R. A. P., M. M., T. H., D. N., and T. A. contributed substantially to data analysis and interpretation; and M. L. N., T. J. H., T. A., A. N., N. J., R. A. P., M. M., D. C., and D. N. contributed substantially to the writing of the manuscript.

Role of sponsors: The sponsor had no role in the design of the study, the collection and analysis of the data, or the preparation of the manuscript.

Other contributions: The authors thank the team at Inworks Innovation Initiative for developing the immersive VR anatomy trainer, including Hayden McClain, MS, Channing Williams, MS, Monica Fong, MS, Chilli Kellaway, BA, and Franchesca Valentin, BA. They also thank Michael Peters, PhD, for permission to use the MRT and for providing the testing materials to the researchers. Finally, they thank Bryan Borg, MD, Vibhu Sharma, MD, Joshua Smith, MD, and York Miller, MD, for testing and providing feedback on the VR anatomy trainer during its development.

Additional information: The e-Appendix, e-Table, and Video are available online under "Supplementary Data."

References

1. Wahidi MM, Herth F, Yasufuku K, et al. Technical aspects of endobronchial ultrasound-guided transbronchial needle aspiration: CHEST Guideline and Expert Panel Report. *Chest*. 2016;149(3):816-835.
2. Haas AR, Vachani A, Sterman DH. Advances in diagnostic bronchoscopy. *Am J Respir Crit Care Med*. 2010;182(5):589-597.
3. Miller RJ, Mudambi L, Vial MR, Hernandez M, Eapen GA. Evaluation of appropriate mediastinal staging among endobronchial ultrasound bronchoscopists. *Ann Am Thorac Soc*. 2017;14(7):1162-1168.
4. Wahidi MM, Hulett C, Pastis N, et al. Learning experience of linear endobronchial ultrasound among pulmonary trainees. *Chest*. 2014;145(3):574-578.
5. Garcia-Robles P, Cortes-Perez I, Nieto-Escamez FA, Garcia-Lopez H, Obrero-Gaitan E, Osuna-Perez MC. Immersive virtual reality and augmented reality in anatomy education: a systematic review and meta-analysis. *Anat Sci Educ*. 2024;17(3):514-528.
6. Barteit S, Lanfermann L, Barnighausen T, Neuhann F, Beiersmann C. Augmented, mixed, and virtual reality-based head-mounted devices for medical education: systematic review. *JMIR Serious Games*. 2021;9(3):e29080.
7. de Faria JW, Teixeira MJ, de Moura Sousa Júnior L, Otoch JP, Figueiredo EG. Virtual and stereoscopic anatomy: when virtual reality meets medical education. *J Neurosurg*. 2016;125(5):1105-1111.
8. Duarte ML, Santos LR, Guimarães Júnior JB, Peccin MS. Learning anatomy by virtual reality and augmented reality. A scope review. *Morphologie*. 2020;104(347):254-266.
9. Stepan K, Zeiger J, Hanchuk S, et al. Immersive virtual reality as a teaching tool for neuroanatomy. *Int Forum Allergy Rhinol*. 2017;7(10):1006-1013.
10. Rogister F, Pottier L, El Haddadi I, et al. Use of Vandenberg and Kuse Mental Rotation Test to predict practical performance of sinus endoscopy. *Ear Nose Throat J*. 2022;101(suppl 2):24S-30S.
11. Zaika O, Boulton M, Eagleson R, de Ribaupierre S. Development of technical skills in simulated cerebral aneurysm coiling. *Medicine (Baltimore)*. 2023;102(11):e33209.
12. Guillot A, Champely S, Batier C, Thiriet P, Collet C. Relationship between spatial abilities, mental rotation and functional anatomy learning. *Adv Health Sci Educ Theory Pract*. 2007;12(4):491-507.
13. Peters M, Laeng B, Latham K, Jackson M, Zaiyouna R, Richardson C. A redrawn Vandenberg and Kuse Mental Rotations Test: different versions and factors that affect performance. *Brain Cogn*. 1995;28(1):39-58.
14. Davoudi M, Colt HG, Osann KE, Lamb CR, Mullon JJ. Endobronchial ultrasound skills and tasks assessment tool: assessing the validity evidence for a test of endobronchial ultrasound-guided transbronchial needle aspiration operator skill. *Am J Respir Crit Care Med*. 2012;186(8):773-779.
15. Maresky HS, Oikonomou A, Ali I, Ditkofsky N, Pakkal M, Ballyk B. Virtual reality and cardiac anatomy: exploring immersive three-dimensional cardiac imaging, a pilot study in undergraduate medical anatomy education. *Clin Anat*. 2019;32(2):238-243.
16. Nicholls D, Sweet L, Muller A, Hyett J. Teaching psychomotor skills in the twenty-first century: revisiting and reviewing instructional approaches through the lens of contemporary literature. *Med Teach*. 2016;38(10):1056-1063.
17. Leppink J, van den Heuvel A. The evolution of cognitive load theory and its application to medical education. *Perspect Med Educ*. 2015;4(3):119-127.
18. Sewell JL, Boscardin CK, Young JQ, ten Cate O, O'Sullivan PS. Learner, patient, and supervisor features are associated with different types of cognitive load during procedural skills training: implications for teaching and instructional design. *Acad Med*. 2017;92(11):1622-1631.
19. Gerretsen ECF, Chen A, Annema JT, et al. Effectiveness of flexible bronchoscopy simulation-based training: a systematic review. *Chest*. 2023;164(4):952-962.
20. Scarlata S, Palermo P, Candoli P, Tofani A, Petitti T, Corbetta L. EBUS-STAT subscore analysis to predict the efficacy and assess the validity of virtual reality simulation for EBUS-TBNA training among experienced bronchoscopists. *J Bronchology Interv Pulmonol*. 2017;24(2):110-116.
21. Nielsen AO, Cold KM, Vamadevan A, Konge L, Clementsen PF. Systematic endobronchial ultrasound—the six landmarks approach. *J Vis Exp*. 2023;198:e65551.