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Assessment of Contemporary Virtual Reality Programs and 3D Atlases in Neuroanatomical and Neurosurgical Education

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Statement of Significance:

The utilization of innovative technologies in medical education has received increasing attention in both undergraduate and graduate medical curricula. Understanding spatial, physiological, and pathological aspects of neuroanatomy are important for medical students and residents, alike. As virtual reality applications and platforms become more accessible to educators, learners, and the general public, such technology now represents a feasible modality of neuroanatomical education. This qualitative observational study compares and evaluates five programs based on the accessibility, breadth of content, and utility for various learner populations.

Objective: Virtual reality (VR) is a growing technology of interest in medical education, particularly as the millennial generation has become the primary learners. We sought to compare the five available and affordable neuroanatomical programs with objective comparisons of the neuroanatomy, format, and target audience.

Methods: The following programs were included: Sharecare VR, Organon VR, The Neurosurgical Atlas 3D Operative Neuroanatomy, BioDigital 3D Human Anatomy, 3D Brain. These programs were selected based on their price ($0-30) and platform (HTC Vive, Oculus Rift, iOS, Google Chrome). The following neuroanatomical categories were assessed: CNS, Cranial Nerves, PNS Skull, and Spine. Neuroanatomical level of detail was scored from 0 (absence of structure) to 3 (operative anatomy). Points were provided if programs included explanations of neuroanatomical relevance, models of pathology & physiology, references, and quiz features. These scores were tallied and compared.

Results: The Neurosurgical Atlas and BioDigital scored highest (22 points each), followed by Organon VR (11), 3D Brain (9), and Sharecare VR (6). The Neurosurgical Atlas had the most detail with a score of 3 in each neuroanatomical category. BioDigital included more, but simpler, models. 3D Brain included simple CNS models, but useful explanations and references. Disappointingly, the VR-exclusive programs had entertainment-only models, scoring only 1 point all model).

Conclusions: The Neurosurgical Atlas is the most relevant and detailed model of neuroanatomy and is most appropriate for resident- or attending-level anatomic review. The remaining programs lacked detailed neuroanatomy limiting their potential for a neurosurgical audience.

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Supplemental content

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Literature on contemporary medical education demonstrates resident physicians who identify as millennials increasingly rely on free online tools such as podcasts and webpages to supplement learning rather than printed texts or peer-reviewed journals.[1] This poses a particular challenge as such resources are often neither fact-checked nor peer-reviewed and may be prone to biases. As the goal of medical education is to train physicians practicing evidence-based medicine, reliance on non-peer-reviewed sources presents a novel threat. While peer-reviewed journals will always serve as the backbone of medical information, the information from such sources must be disseminated in a way that actively engages new generations of medical learners.

The average age of entering neurosurgery residents is 30.5 years, making the millennial generation the target demographic in neurosurgical education.[2] Defined as those individuals born between 1982 and 2000, the millennial generation is described as "technologically native," having grown up in a world dominated by instant access to information and constantly changing technology.[3] Studies have shown that being raised in this environment has drastically shifted the educational needs of its learners, such that they need hands-on, experiential learning as opposed to reading long text.[3] As these learners enter neurosurgical training, it is advantageous for surgical education to adapt to this new landscape by enhancing curricula through active, extra-operative methods of surgical education. These methods rely upon active learning, the educational theory in which students engage in reflection, self-assessment, problem-solving, and attaining knowledge through participation.[4] These modes of education have continually been shown to boost knowledge retention and application.[5] One particularly attractive active learning modality for neurosurgical education is virtual reality (VR).

Prevalence of VR utilization has dramatically increased over the past 5 years as evidenced by the development and release of multiple realistic surgical emulators. The availability and ease of use of major VR platforms, such as the HTC Vive and Oculus Rift, have substantially reduced barriers preventing neurosurgery programs from implementing VR curricula in resident education. These VR platforms provide neurosurgeons-in-training the opportunity to recreate surgical neuroanatomy within minutes, virtually enter an operating room (OR) and practice routine cases, learn new ones, or plan for surgeries using patient MRIs. Early analyses of this training modality look promising, as VR has been shown to improve technical ability and reduce the time spent teaching intraoperatively, potentially improving patient care.[6] Neurosurgical trainees are likely to be familiar with three-dimensional (3D) modeling, thus the utilization of 3D models via VR is intuitive. These findings make a compelling argument that VR has a place in neurosurgical education; however, as a young, developing technology, proper planning is required to ensure useful implementation in neurosurgery programs—particularly regarding education.

While there are many uses for VR in medical education, one of the most attractive is for teaching neuroanatomy. At long last, the difficulty of emulating actual neuroanatomy in a clinically meaningful way can be addressed using high-fidelity VR programs. This usage is particularly important in neurosurgery, as mastery of neuroanatomy is essential for any practicing neurosurgeon. Studies demonstrate the ability to visualize and manipulate neuroanatomical structures in 3D space can boost trainee confidence and performance in identifying structures, thus directly linking VR to intraoperative skill.[7] These findings further highlight the value of VR in neurosurgery training, yet with the range of platforms and programs available, it can be difficult to find a starting point for implementation.

This article aims to provide in-depth analysis of anatomical programs currently available to the public as to encourage the utilization of VR technologies for the appropriate learner levels. Currently, there are only a handful of VR anatomy programs, none of which have been critically appraised, and a greater number of iOS anatomy programs. Although surgical planning neurosurgical VR programs have been developed, this paper will not assess them due to barriers of cost and accessibility. Rather, we sought to compare the five readily available and affordable programs with objective comparisons of the available neuroanatomy, educational format, and target audience. The technical specifications and the strengths & weaknesses of each program are discussed, with a target audience recommendation provided.

Methods

Five anatomy programs with prices ranging between $0 and $30 were utilized in this study: Sharecare VR (Sharecare Inc), Organon VR (Medis Media), the Neurosurgical Atlas (Neurosurgical Atlas Inc), BioDigital 3D Human Anatomy (BioDigital), and 3D Brain (Cold Spring Harbor Laboratory). Programs were analyzed from May to August 2019. Although there exist more virtual reality and 3D anatomy programs available for public purchase, these programs were selected due to their relatively large amount of neuroanatomical structures, and low cost (< $50). Programs were accessed utilizing the HTC Vive Pro (HTC Corporation), iPad Mini 4 iOS 13 (Apple Inc), or Google Chrome web browser (Google LLC; Alphabet Inc). All platforms and programs utilized the most current firmware release at time of analysis. All devices were owned by co-authors or School of Medicine Department of Neurosurgery..

Programs were tested based on parameters of cost, ease of use, various anatomical structures, representations of physiological and pathological processes, and curricular content (Supplemental Table 1). The point structure was designed to best compare the anatomic detail of the models as they might meet the needs of a high-functioning neurosurgery resident. This scoring system is not validated but was prospectively designed to evaluate the sophistication of educational VR programs based on author experience and expectations of pedagogic tools. A single rater used each program and analyzed the included neuroanatomy, assigning points utilizing the scoring system. Points were given for each level of neuroanatomical information that the software included, with the total points tallied and the programs compared. The cost of each program, availability (i.e. how to acquire each program), and platform are reported as well. These scores were tallied and compared.

Definitions:

Mix-and-Match: the ability to overlay separate anatomical models such that you can see both at the same time.

M*anipulation:* The ability to move 3D models around an axis/axes.

F*ixed axis*: you can only move models along predetermined axes/paths.

Results

Score reports are summarized in Table 1. The Neurosurgical Atlas and BioDigital scored the highest at 22 points. These programs were easy to use and provided a wide range of 3D structures. The Neurosurgical Atlas was extremely high-fidelity, detail-oriented, and free. Furthermore, it was targeted specifically at the neurosurgical audience. BioDigital was $9.99/year and scored an equivalent score mainly due to a larger number of available structures in different categories such as the spine, peripheral nervous system, and pathology. It was not as detailed as the Neurosurgical Atlas but had useful features such as a quiz function. Organon VR had many different structures but was severely limited in its ease of use and functionality. It was one of the only true VR programs but was difficult to use and cost the most at $29.99. 3D Brain was an easy-to-use and informative neuroanatomy program for iOS but was limited in its functional use and lack of dynamic models. Sharecare VR was the other true VR program but was the most simplistic and was mainly made for entertainment versus educational purposes. These comparisons can be seen in Table 2. The total number of labeled structures are compared in Figure 1; notably, Organon VR was

Table 1. Score reports

	Sharecare VR	3D Brain	Neurosurgical Atlas	BioDigital	Organon VR
Specifications					
Cost	Free	Free	Free	$9.99/year	$29.99
Availability	Steam	App Store	Online	App Store	Steam
Platform	HTC Vive, Oculus Rift	iPad	Online	iPad	HTC Vive, Oculus Rift
Ease of use	1	1	3	3	1
Structure					
CNS	1	2	3	2	1
Vasculature	1	0	3	2	1
Cranial Nerves	0	0	3	2	1
	0	0	0	2	2
Skull	1	0	3	2	1
Spine	1	0	0	2	1
Physiology	1*	0	0	1	0
Pathology	0	0	1 (AVM)	3	0
Curricula					
Information	0	3	3	1	3
References	0	3	3	0	0
Quizzes	0	0	0	2	0
Total	6	9	22	22	11

not included as isolating each structure was not possible secondary to the difficulty of use.

Sharecare VR

Sharecare VR is a free virtual reality software available for the HTC Vive and Oculus Rift. Users enter a VR space and manipulate neuroanatomical structures in predetermined motions. This program scored 6 points. Each of the included structures (CNS, Vasculature, Skull, Spine) earned 1 point due to simplistic nature and lack of detail (for instance, vasculature models included only nine labeled vessels). Sharecare scored 1 point for Ease of Use due to difficulty in manipulating models. Models were set on fixed axes and users could not freely manipulate object orientation. Sharecare lacked models of the cranial nerves, peripheral nervous system, and pathological variants. Only one physiology model was present, which demonstrated the flow of cerebrospinal fluid through cerebral ventricles. There was no information about structure-function, no included references, and no quiz feature.

Benefits: Impressive immersive; the VR environment makes it seem like you are in the same room as these structures.
Negatives: Functionality: models cannot be rotated to the user's desire, lack of mixing and matching, all structure labels are not visualized (this is especially true with the vasculature) and models cannot be appreciated in a realistic size. Detail: there are very few structures, and the limited viewpoints of these structures make them difficult to use in a robust educational capacity.
Recommendation: Best for someone with no knowledge of neuroanatomy. Not useful as an educational tool, but more aimed for leisure. Not recommended for patient or provider education.

3D Brain

3D Brain is a free application developed by the Cold Spring Harbor Laboratory available on iOS devices. The app offers 29 models of brain structures users can manipulate on the X and Y-axis. 3D Brain scored 9 points. Two points were awarded for the CNS models, which highlighted several important functional brain structures (basal ganglia, cerebellum, ventricles, etc.). 3D Brain earned the rest of its points from its Ease of Use (1 point), Information (3 points), and References (3 points). Although this application was easy to navigate, viewing angles were limited by the 2-axis system, users were unable to mix-and-match different structures, and users could not manipulate the models with labels turned on. 3D Brain was awarded most points for robust academic content in the Information and References categories. The information provided for each structure included an overview of structure-function, a case study, associated functions, cognitive disorders, and descriptions of lesion pathology. For References, each structure included links to relevant review articles with their PMID and associated links for further reading.

Benefits: Simplicity: intuitive menu bar, structures can be identified and isolated easily. Information: the descriptions and references are a great inclusion.
Negatives: Functionality: No mix and match feature (only one structure can be visualized at a time), models cannot be manipulated with labels turned on, and low-resolution models.
Recommendation: A great tool for medical students learning basic neuroanatomy. This could be a useful educational tool for patients and their families.

The Neurosurgical Atlas

The Neurosurgical Atlas is a free website developed by neurosurgeon Dr. Aaron Cohen-Gadol, MD which recently unveiled 3D Operative Neuroanatomy models for neurosurgical education. Current offerings include models of the brain, skull, vasculature, and cranial nerves. Although these models were designed to be visualized using computers and tablets, they can also be seen and manipulated via VR systems. The Neurosurgical Atlas scored a total 22 points, with all of its included structures earning the highest score possible (3 points). These structures were scored highly due to their detailed, complete nature which also highlighted relevant operative neuroanatomy. Models earned 3 points for Ease of Use because each model was easily manipulated in all directions and loaded quickly. There was only one model of neurosurgical pathology (arteriovenous malformation). Each model was integrated into an informative article explaining the importance of neuroanatomical relationships with included citations listed at the bottom, thus giving The Neurosurgical Atlas scored 3 points in both Information and References. There is no quiz feature on the models.

Benefits: Detailed models (includes the skull, cerebrovascular, cavernous sinus, brainstem, and pterional craniotomy anatomy), peer-reviewed resources: *Rhoton, Journal of Neurosurgery, Neurosurgery*; Ease of Use; the models are easy to manipulate, load quickly, and the annotated models are labeled clearly. Structures can be hidden to the user's preference.
Negatives: Only 18/34 of the models have annotations and there is no mix and match feature. At time of review, there were no infratentorial, and ventricular models despite being listed by the website.
Recommendation: Attendings, residents, medical students. Great models of the skull, vasculature, and brainstem that can be used as an educational tool for all.

BioDigital 3D Human Anatomy

BioDigital 3D Human Anatomy is a subscription-based iOS application. For $9.99/year, users can view and manipulate 3D models of every organ system. The iPad application was utilized in this study. The program scored a total 22 points. The wide range of nervous system models, which included the CNS, vasculature, cranial nerves, peripheral nervous system, skull, and spine earned the majority of BioDigital 3D Human Anatomy's points. These models all scored a 2 because they were detailed, yet not enough for surgical training. The interface was easy to use, allowing 360° manipulation and a simple, customizable layout (3 points). A score of 1 point was given for the included physiology models, which were limited to simple demonstrations of neurotransmission. BioDigital 3D Human Anatomy included several pathology models (aneurysms, whiplash injury, carpal tunnel syndrome, stroke, etc.), earning 3 points in Pathology. Information was scored at 1 point; each structure only listed the first line from a respective Wikipedia page. Furthermore, no references were provided through the app. The application included a quiz feature that allowed users to choose the difficulty level, number of questions, and then had users hunt for structures in each model.

Benefits: completeness; many different models, drawing tool, pathology, a quiz feature
Negatives: lack of peer-reviewed information, no mix, and match feature
Recommendation: Good reference for pre-clinical medical students. The quiz function and the number of available models make this especially useful. The physiology/pathology models could be used for patient education, but many of them are very simplistic.

Organon VR

Organon VR is a $29.99 VR anatomy atlas available for the HTC Vive and Oculus Rift. The app offers models for each human organ system. Within the nervous system, users can view and manipulate the brain, vasculature, cranial nerves, PNS, skull, and spine. The neuroanatomy was very basic and only included large brain structures (cerebral hemispheres, cerebellum, cingulate gyrus, etc.) and therefore scored 1 point. The skull and spine were similarly simple (1 point). The vasculature, cranial nerves, and PNS were more detailed with major branches of each included and thus earned a score of 2 points. Organon VR was difficult to use, requiring the user to manually grab each structure they wanted to hide in order to visualize deeper structures. There was an inability to manipulate models across all three axes and forced the user to physically walk around the model to look at different angles. Furthermore, the inability to zoom made viewing small structures difficult. There were no models of physiology or pathology. The information included for each structure was useful, but there were no included references; thus, scoring 2 points for Information and no points for References. Information about associated pathologies was included, but there were no models of said pathology.

Benefits: Immersive, High resolution
Negatives: Extremely difficult to use
Recommendation: This app would be most useful for entertainment purposes only. At its relatively high price point, this app would be difficult to use as a learning tool. There is not enough detail in terms of neuroanatomy and manipulating the models was extremely frustrating. Each structure was very small with no zoom capability and required the user to grab each structure and move it out of the way to see the deeper structures.

Discussion

After spending a significant amount of time exploring these neuroanatomical programs, our scoring system identified Neurosurgical Atlas as the most useful for neurosurgical education. This atlas provides several high-fidelity 3D models of relevant operative neuroanatomical structures for which neurosurgical trainees require mastery, such as the skull, cerebrovasculature, the cavernous sinus, brainstem, and pterional craniotomy anatomy. In addition to 3D models, this atlas provides valuable information on operative tech-

Table 2. Qualitative summary of pros,cons, and ideal audience by program

	Neurosurgical Atlas	BioDigital	Organon VR	3D Brain	Sharecare VR
Pros	- Ease of use - Advanced neuroanatomy - Peer-reviewed information	- Quiz Feature - Good neuroanatomy - Many non-CNS models	- Immersive experience - Good descriptions - Good non-CNS models	- Ease of use - Citations for descriptions - Relevant review articles	- Immersive experience
Cons	- No mix and match - Limited model annotation - Lack of pathology	- Lack of peer-reviewed information - Simple models	- Difficult to use - Limited neuroanatomy - Cannot zoom	- Limited manipulation - No mix and match	- Limited neuroanatomy - Limited manipulation - No mix and match
Audience	- Attendings - Residents - Medical students	- Pre-clinical medical students - Patient education	- Lay-persons	- Pre-clinical medical students - Patient education	- Lay-persons

niques and indications for surgical intervention. The information included with each model comes from trusted resources such as the Rhoton Collection and peer-reviewed neurosurgical journals such as *Neurosurgery* and *The Journal of Neurosurgery*. Furthermore, these models were extremely intuitive, easy to access, and free. All of these factors make the Neurosurgical Atlas the premier tool for neurosurgical education. Yet, as impressive as the Neurosurgical Atlas is, our exploration of other available programs using our scoring rubric sheds light on potential directions for improvement.

Using our scoring system, BioDigital performed well (total score = 22) due to its large number of models and functionality, both of which the Neurosurgical Atlas could look to incorporate. As spinal surgery represents a substantial proportion of neurosurgical training, the potential benefits of easily accessed, high-fidelity spinal models are readily apparent. Models of pathology, such as acoustic neuromas, meningiomas, ependymomas, and aneurysms, would be useful in teaching surgical approaches by allowing learners to better appreciate important neuroanatomical aberrancies. Regarding functionality, BioDigital's program offered a useful quiz function allowing users to search for structures in the model to assess their knowledge base. A similar function with the Neurosurgical Atlas would be a welcomed addition, especially if it quizzed learners from different cranial approaches. This application of knowledge would actively engage learners in a way that mimics the cognitive skills utilized intraoperatively. However, The Neurosurgical Atlas is continuing to improve with time, as they continue to put out new models. Most recently, models of the supratentorial anatomy, cavernous sinus, and pterional approach have been unveiled. Since the Neurosurgical Atlas is managed by a board-certified practicing neurosurgeon, it is no surprise that this program targets the neurosurgery audience well. These improvements show continued commitment to neurosurgical education and offer a great deal of excitement for the future.

From this study of five easy to access and affordable neuroanatomical programs, we have gained a greater appreciation for the current landscape of virtual reality and it is apparent that VR is limited by several key factors when it comes to neurosurgical education: passive learning, ease of use, and time & space requirements. The current VR and 3D models of neuroanatomy still have users adopting a passive role as an observer rather than an actively engaging role in which one can manipulate neuroanatomical structures in a way that builds the cognitive relationships necessary to be a skilled neurosurgeon. If developers incorporate functions like quizzes, interactive lessons, and procedural practice into VR applications, then users will be engaged in an individualized way that will provide the greatest benefit for millennial learners. This method of active education leads to higher rates of information retention and better application of the information.[5] Furthermore, this mode of education is the one that is best suited for the millennial generation as their goal-oriented, team-oriented, and technologic skill favors the use of active learning methods over passive methods.[8]

For VR to become more widely utilized in neurosurgical training would require a substantial improvement in the ease of use. The two major VR programs, Sharecare VR and Organon VR, included in this review were the only neuroanatomical programs available on the Steam Store (Valve Corporation) at the time of analysis and both scored lower (6 and 11, respectively) than the Neurosurgical Atlas and BioDigital. The programs were hard to navigate and provided little use for neurosurgical education. Due to the time constraints of neurosurgical residency, a program that is not intuitive, difficult to use, and provides no clear improvement over traditional learning methods will not be widely adopted by learners. Luckily, this component of VR should continue to improve as technology further develops. As more users and developers attempt to tackle these issues, we believe the benefit for learners will only continue to grow.

The final hurdle that must be overcome to adopt VR as a tool in medical education, and possibly the most difficult, are requirements of time and space. The HTC Vive Pro VR system's dedicated floor space requirement (5 ft x 6.5 ft) and higher price point currently limit widespread adoption and utilization. Furthermore, the time required to boot the system and run programs is likely incompatible with typical neurosurgical resident schedules. In contrast, one of the major benefits of the Neurosurgical Atlas and BioDigital was how quickly these models could be accessed, as users could pull them up on their phones or desktop computers, making daily use by learners easier. Due to the limited time frame that residents and medical students have to review the relevant neuroanatomy of cases, it would be useful to have quick, reliable references broken down by procedure as well as the deeper, active learning functionality that can be used during the study.

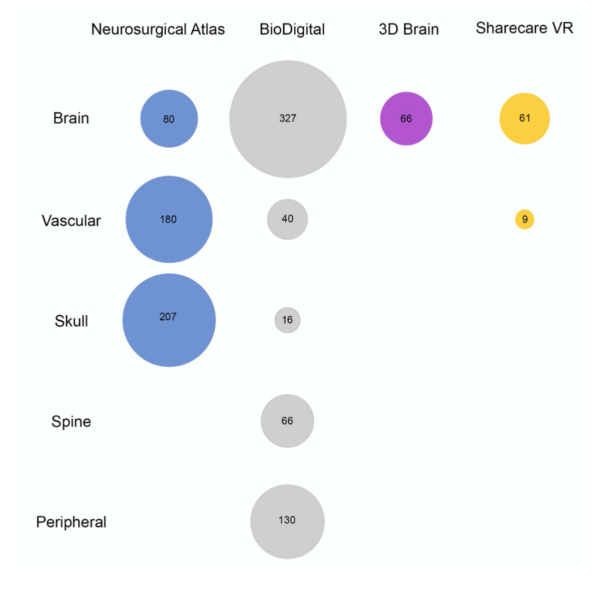

Figure 1. *Labeled neuroanatomical structures included in each program*. Neuroanatomy models within 4 of the 5 programswere analyzed with each labeled structure being recorded. The total number oflabeled structures can be compared among the programs by utilizing the relativesize of each circle. Organon VR was not included due difficulty in isolatingstructures.

This study mainly serves as a review of the contemporary offerings of VR programs with potential neurosurgical education applications. As to be expected of literature focusing on rapidly developing technologies, newer versions of these programs are available at the time of publication and each warrants further investigation; however, this review serves as the only attempt at characterizing VR as a tool in neuroanatomy education for neurosurgical residents in recent years. To further investigate modalities and outcomes of VR in neurosurgical education, we intend to pursue additional studies assessing outcomes and other important comparative criteria.

Conclusion

As technology continues to advance in medical education, reliable, accurate, peer-reviewed information must be disseminated in a way that efficiently reaches the emerging audience and workforce—millennials. Similar shifts in medical education are being seen across all specialties, yet the field of neurosurgery offers a unique opportunity to integrate new technologies for medical education as a 3D understanding of neuroanatomy is essential for improving surgical skills. The Neurosurgical Atlas is a valuable tool for neurosurgical trainees and is continuing to improve daily. VR remains in technological infancy within the contexts of medical and neurosurgical education. However, from this analysis of the readily available programs, there is already investment from multiple sources and potential for a promising future for the implementation of VR technology as a highly efficacious pedagogic modality in neurosurgical education.

Limitations

This study is limited by the low number of available low-cost programs with detailed anatomy, as well as an absence of a previously validated scoring system. While our scoring system is not validated, we feel a validated system would add little value to this observational investigation as no two programs were similar or close enough in detail to have true comparisons made. Finally, this analysis did not measure learning outcomes of students or residents using any of the included programs, and instead focused on features of programs likely to correlate with pedagogical value.

ARTICLE INFORMATION

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