Review of Learning Tools for Effective Radiology Education During the COVID-19 Era

David Chen, BS, Andres Ayoob, MD, Terry S. Desser, MD, Aman Khurana, MD

Coronavirus disease 2019 (COVID-19) has significantly disrupted medical education around the world and created the risk of students missing vital education and experience previously held within actively engaging in-person activities by switching to online leaning and teaching activities. To retain educational yield, active learning strategies, such as microlearning and visual learning tools are increasingly utilized in the new digital format. This article will introduce the challenges of a digital learning environment, review the efficacy of applying microlearning and visual learning strategies, and demonstrate tools that can reinforce radiology education in this constantly evolving digital era such as innovative tablet apps and tools. This will be key in preserving and augmenting essential medical teaching in the currently trying socially and physically distant times of COVID-19 as well as in similar future scenarios.

Key Words: SARS-Cov-2; Coronavirus; Radiology; Medical education; Electronic teaching tools; Online education.

INTRODUCTION

In recent decades, there has been a shift in medical teaching from passive didactic formats to more active learning strategies (1–4). This is due to the greater education yields produced by these active learning methods compared to passive learning (5–8). There has also been a gradual trend towards moving certain aspects of education online due to the practicality and cost-efficiency offered (9,10). These online modules are not chosen because of their ability to outperform traditional in-person teaching models but because they can provide additional benefits when paired with supplementary active learning strategies, such as lessening geographical and temporal constraints upon students, allowing for a greater range of material dissemination by various online platforms, and increasing adaptability based on the needs of each student (10–12).

During the novel coronavirus disease 2019 (COVID-19) pandemic, there has been an abrupt change in the curricula of medical institutions (13). The most effective method for curtailing the rapid spread of the virus is through physical distancing and therefore the online mode of teaching has seen a sudden surge in its use (14). With this shift to online formats, schools unaccustomed to this methodology are at risk of defaulting back into the primarily didactic passive lecturing styles of the past, such as simple uploads of PowerPoint lecture videos etc. (15). This could prove problematic for the current generation of future physicians as the training they receive will be less interactive compared to the traditional, in-person, small group-based teaching methods available to their predecessors and successors who trained in normal societal conditions.

To retain educational yield on par with levels of recent times, creative strategies that involve active learning through digital technology are necessary. Ideas have already been proposed on how to make learning more engaging, effective, and appealing during this time for students such as gamification, synchronous case reviews, and flipped classroom techniques (16–18). Another such method is the strategy of microlearning which can address the concerns of passive learning formats and recover educational yield lost with an online transition. Microlearning revolves around lessons utilizing small, bite-sized amounts of information that is easily digestible for students in one sitting and taught in a step-by-step manner. This strategy is primarily focused upon making short and readily repeatable connections between small learning units which hastens development of critical thinking and clinical reasoning. Microlearning has commonly been implemented inside digital teaching frameworks and can have significant performance benefits with examples such as mobile apps for nursing, interactive online case-based medical trainings, social media group learning, and more (12,19,20). Microlearning has been coupled with visual learning tools to further leverage teaching benefits (21–23).

Acad Radiol 2022; 29:129–136

From the University of Kentucky College of Medicine, Lexington, Kentucky (D.C.); Department of Radiology, University of Kentucky Chandler Medical Center, 800 Rose St, HX 316, Lexington, KY 40536 (A.A., A.K.); Department of Radiology, Stanford University, Stanford, California (T.S.D.). Received June 16, 2021; revised October 11, 2021; accepted October 12, 2021. **Address correspondence to:** A.K. e-mail: aman.k@uky.edu

https://doi.org/10.1016/j.acra.2021.10.006

This is relevant for radiologists in training because they need to develop a high degree of visual acuity and familiarity with a multitude of imaging features to differentiate the spectrum of normal from pathological conditions and be prepared for independence in the field. Visual learning tools like 3D imaging software have been shown to improve diagnostic abilities in undergraduate radiology (24).

This article will introduce digital learning, review the efficacy of applying microlearning and visual learning, and demonstrate some of the tools that can serve to bolster medical and radiology education during this era where the newer teaching strategies are in demand.

IMPACT OF COVID-19

In response to the novel COVID-19 pandemic, the primary goal of many countries was to protect the most vulnerable from infection and decrease major surges that overwhelm hospital capacities. To accomplish this, many nations' responses included public health initiatives like handwashing, mask-wearing, contact tracing, and social distancing (25). One of these initiatives involved minimizing viral transmission risk by mandating social distancing practices in areas where large groups gather such as educational institutions. At the height of this response on April 24 2020, approximately 1.48 billion learners around the world had education impacted by COVID-19, which represents 84.5% of the entire global education population (26,27).

As a result, medical institutions in all fields were forced to implement changes to their teaching curricula on very short notice (28). For preclinical medical students, their anatomy and radiology curricula were unable to employ previously commonplace teaching methods of the past like face-to-face teaching, cadaver dissections, ultrasound practice, and laboratory sessions (15). The legacy of curricular gaps has the potential to lead to struggles within their clinical years and shortcomings in their foundational knowledge that will be carried forward with them long term. The primary radiology pedagogical methods for medical students in clinical years before the pandemic held great weight for in-person teaching methods such as hands-on workshops, team-based learning, and clinical shadowing which have been difficult to keep afloat during the pandemic (15,29). In respect to radiology residents and fellows, the pandemic resulted in academic radiologists spreading out within their medical facilities or in their homes. This rapid change from the traditional shoulder to shoulder workstation approach has disrupted teaching which previously involved learning from radiologists on rotation and in-person teaching formats like hot-seat type questioning, reviewing peers' scans, and hands-on procedures (14).

With respect to radiology residents and fellows, their educational part of the training has also been deprioritized in favor of providing urgently needed clinical service amid the growing pandemic. Residents and fellows may now feel as though their role is more ambiguous due to experiencing lower volumes of elective and nonurgent clinical procedures (30,31). Learning-related travel to onsite radiology meetings and certain clinical experiences have been curtailed, which can ultimately result in a reduced knowledge base and hindered advancement to independent practice (14,28).

Nevertheless, one upside to the disruptions of the COVID pandemic was the forced re-imagining of radiology operations, including clinical care, and teaching, necessitated by social distancing mandates (32). Over time, strategies have emerged for digital teaching and remote learning that offer more opportunities for scheduling flexibility, work-life integration, and access. For example, video conferencing over platforms such as Zoom enable sharing of educational conferences in real time with trainees dispersed among multiple sites such as outpatient clinics, affiliated hospitals, or even providing childcare at home. Interesting case or "hot-seat" type conferences can potentially be held with multiple training programs sharing cases with one another, and didactic conferences can be archived for trainees to view on demand when convenient. With "necessity as the mother of invention," new paradigms such as these may ultimately prove to be advantageous and sustainable even after the COVID pandemic subsides.

DIGITAL LEARNING

Digital learning has been a growing trend in recent years but now has been thrust into the mainstream spotlight with the shift of teaching onto online platforms due to safety concerns of the COVID-19 pandemic.

Even before the pandemic, medical schools were put under increasing pressure to adopt digital methods due to decreasing funding, increased geographical dispersal of students, rising student body populations, and competition from other global schools advancing their teaching efficacy (33). In terms of educational yield, these distance learning environments are favored because, when using interactive means, they can have equal or better outcomes than similar in-person methods but also offer additional benefits over in-person settings (10). Before the pandemic required physical distancing, eLearning's main advantages came from its potential to offer greater degrees of convenience, customization, and cost-efficiency compared to that of a traditional classroom. Some schools have also employed web-based teaching in the past as a solution to the problems of ensuring a consistent curriculum across their spread-out facilities (34). In radiology teaching, web-based methods have shown greater educational yield for image interpretation and case studies (9,35-37). The main disadvantages with supplementing traditional curricula with digital learning portions involved the learning curve to utilize the technology and the extra financial burden that exacerbates the conditions of less socioeconomically fortunate students (38).

There are two main differences in the digital learning of the present compared to that of the past. One is that medical learners will have less exposure to core in-person activities such as interventional procedures, conferences, and patient encounters. The other difference is that the institutions that implemented this digital methodology in the past were able to carefully craft a curriculum to effectively teach their students whereas those affected by the pandemic did not have enough time to implement it. Reliance upon passive didactic eLearning in place of active learning methods can jeopardize the future of not just radiology learners but those of all disciplines as this sudden shift impacts the essential areas of education (28,29,39). Active learning has been defined as "involving students in doing things and thinking about the things they are doing" (40). In contradistinction to passive listening during a traditional lecture, students are engaged to think at higher cognitive levels through purposefully crafted learning activities. Active learning has been shown to have several benefits including improved learner attention and increased learner motivation.

In regards to this online transition, various active learning methods such as a) procedural simulations, b) case-based learning, c) gamification, and d) flipped classroom teaching have been popular suggestions (41,42).

For many hospitals, a) procedural simulation equipment can be split into time blocks for small-groups or individual use to maintain physical distancing which has re-sparked interest in this field in the COVID-19 era. Ideas to move simulations outside of the hospital like computer-based virtual reality have also been proposed which could also serve towards both retaining educational yield within pandemic times but also potentially add more hours of practice to previously constrained training areas like interventional radiology and surgery (43). b) Case-based learning (CBL) is a method of teaching in which active learning occurs in the context of clinical cases. CBL "links theory to practice, through the application of knowledge to the cases using inquiry-based learning methods" (44). It helps prepare students for clinical practice through emphasizing problem-solving and clinical reasoning. c) Gamification uses game design elements, such as point systems, leaderboards, badges, and rewards, in traditional nongame contexts (45,46). Regarding education, game design elements can be applied to existing learning activities to facilitate achievement of the activities' learning objectives (47). Gamification has been applied to education in an effort to improve learning outcomes by fostering motivation to learn, increasing engagement and interaction, providing real time feedback to the learner, and lessening learners' fear of failure (48). d) Flipped classroom teaching is a "pedagogical approach in which instruction moves from the group learning space to the individual learning space and the resulting group space is transformed into a dynamic, interactive learning environment where the educator guides students as they apply concepts and engage creatively in the subject matter" (49). With flipped teaching, students are introduced to material before group instruction occurs in the classroom. Pre-class material can be delivered through a variety of methods such as podcasts, screencasts, or readings from books or articles and can be learned by students at their own pace. The classroom or group space used for student-centered active learning activities is designed to simulate higher-order cognitive skills and demonstrate clinical relevance. This format maximizes use of face-time with the instructor, fosters deep learning through engagement, illustrates clinical application of material, encourages peer learning and knowledge sharing, and increases student ownership of the learning process (50). Flipped teaching has been studied across the educational spectrum from secondary to professional schools. Benefits to flipped teaching include improved student satisfaction, increased attendance, and decreased failure rates (51).

Digital learning alone is usually not enough and therefore coupling with microlearning strategies increases the palatability and breadth of these teaching methods as described in detail in the following section.

MICROLEARNING

Microlearning is a teaching methodology that involves condensing learning units into an appropriate amount of information to achieve specific short-term learning goals. This methodology gives users more opportunities to learn whenever convenient to them as they no longer are restricted by lengthy material that requires large blocks of time.

This strategy is more readily implemented into online formats rather than in-person formats due to the individualization offered. In a traditional lecture class, the instructor must consider the progression of all learners together and the course would progress without skipping information. In a digital format, the learner is progressing at their own pace so they can decide the time allocation based on their familiarity with the topic/topics. This allows the usage of microlearning specific subject blocks that the individual deems right for themselves which increases information retention compared to spreading equal amounts of time over all subjects and allows for students to feel increased satisfaction as they possess more control of their schedule (19).

Microlearning's increase in learning efficacy stems from its utilization of short learning periods and small blocks of information. Learners are able to repeat previously learned sections in shorter bursts of time which according to cognitive load theory, allows for more rehearsal, stronger neural network connections, and more conversion of short term to long-term memory (52). Due to these advantages, microlearning-based formats have seen increased use as a refresher before undertaking rare, new, or difficult procedures to promote safety and refine care (12).

There is also the benefit of increased engagement from allowing new out-of-classroom ways to have students work together in familiar digital settings like online or social media (53,54). Microlearning has been seen to have a significant advantage in reaching a greater audience through platforms like social media because of an increased ease at grabbing and keeping one's attention through these short and concise formats. This has led to studies designed around incorporating microlearning formats to initially draw in interested learners and lead them towards teaching methods that are more detailed like full online modules and courses to balance the measured quality of continuing medical education outcomes (55).

A disadvantage brought about by microlearning concerns the discomfort felt by traditional teachers having to switch and learn the emerging digital technologies commonly employed. Another worry is the potential for learning to become too passive when formats such as podcasts are recorded and relied upon as the main teaching material and not supplemented with active lessons (56). Inequalities also exist as not all students possess the same degree of access to technologies which is something universities must consider and account for when implementing these strategies (38). Privacy concerns exist for faculty members as some may not be aware that policies at their institutions consider this online course material as employer property. This could be worrisome if these materials become reused and outdated which would poorly reflect upon the creators so guidelines should be clearly made for instructors' development purposes (12).

A range of previous studies have endorsed the efficacy of using microlearning techniques for health care professionals. Social media formats have been positively received such as 5 Minute Medicine which creates short links upon platforms such as Twitter and YouTube to view common disorders internal medicine residents would encounter in their patients (57). Another such usage of digital social media platforms involves the Chinese Sina Weibo platform similar to Twitter, where students completed case studies in groups and addressed disease states, drug information, patient plans, and more which was seen to improve student interaction and communication (58). Mobile devices have also been utilized to deliver supplemental text messages after class to students about pharmacological information in a way to promote repetition of cardiovascular medications which showed significant improvement compared to those students that did not participate (59). Another model applied within microlearning is just-in-time-training which provides immediate information at moments where it is needed such as letting medical students watch these videos right before they were required to perform wrist splint procedures which was seen to decrease overall learning time, bolster performance, and can provide immense value to remote areas of the world where trained health professionals or educational resources are scarce (60). Another study made use of digital recording technologies by creating audiovisual screencasts of embryology for medical students to help supplement the course material and allow for quick reviews outside of class (61).

The utilization of microlearning often comes with supplementary visual learning cues to further leverage the teaching benefits (21-23) which are discussed below.

VISUAL LEARNING

Visual learning has long been used as a supplementary tool to teach a variety of skill levels ranging from young children to medical professionals (62,63). An inherent advantage of visual teaching is allowing the learner the ability to utilize dual coding of information into memory via both verbal association and visual imagery, which aids learning (64).

For radiology, the ability to have effective visual learning tools in place has been seen to significantly enhance learning and engagement (24,65,66). The concept of drawing and sharing learned information has been shown to have efficacious mnemonic properties through the utilization of elaborative processing (67). The act of drawing out learned information is not a new concept, but what is notable is the increased ease of drawing and sharing this information on digital platforms with no physical constraints. In recent years, technological innovations have made readily available resources for visual learning in radiology like tablet drawing applications and 3D human atlases which allow increased comprehension of difficult anatomy (68).

Education costs can be further decreased through the usage of online visual learning tools like 3D Human atlas technology, which can help conceptualize anatomical areas without the need for expensive cadaver dissections nor the safety risk of caustic chemicals (33). The 3D atlas technology additionally can allow students to view past what is feasible in traditional cadaver labs by giving them microdetails of anatomical structures, joint movements, muscle attachments, and muscle actions. Compared to learning these anatomical concepts from a 2D textbook, the 3D atlases allows the ability to add or remove layers and rotate the anatomical structures in real-time to gain a greater sense of the structure's three-dimensionality (24).

Visual learning can be readily introduced through iPad® tools like Procreate®, Visible Body Human Atlas®, etc. The following sections will highlight the features of the Procreate® drawing tool and Visible Body Human Atlas® and its application in digital radiologic microteaching/microlearning. In the recent decades, websites such as StatDx® and Radprimer® have been popular and successful by combining the previous methods of digital, visual and microlearning opportunities for learners to complete on their own time with directed questions and links to topics while providing artistic renderings of pathologies to assist in understanding various pathologic entities and anatomy. A few of these visual learning applications used in day-to-day teaching at our medical center are introduced in the following.

VISUAL AND DIGITAL LEARNING TOOLS HIGHLIGHTS

Procreate®

Tablet drawing apps such as Procreate® are very commonly used by artists but are excellent for creating radiology figures. It includes various drawing tools such as brushes, pencils, charcoals etc. to create the perfect anatomical graphic and an eraser tool to edit a pre-created anatomical graphic to highlight different anatomical variants or pathological entities when creating teaching material (Fig 1A). Multiple layers can be embedded in the same figure for added functionalities such as highlighting and editing specific portions of the figure (Fig 1B). These features are also highlighted by this example of perianal fistulas which was achieved by copying and pasting the same coronal anatomical graphic multiple times in this figure and then drawing out the different pathologies (perianal fistulas) for comprehensive teaching (Fig 2). Crisp

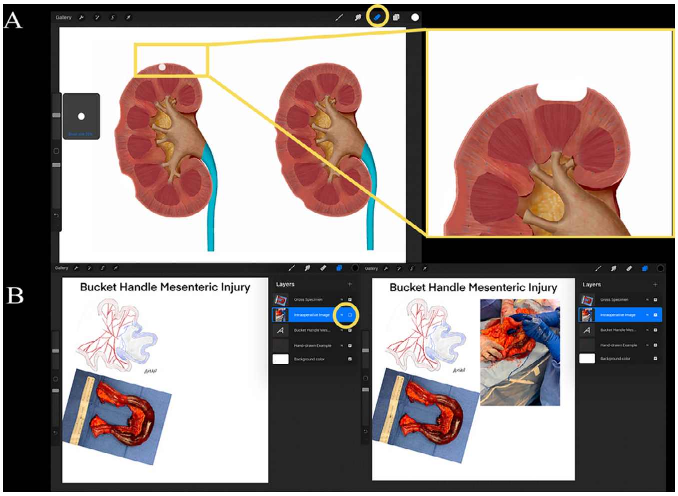

Figure 1. Procreate® erasing and layering: (A) Eraser functionality (circle) to erase content from an anatomical graphic to highlight certain pathological processes, for example differences between renal scarring & fetal lobulation in the left graphic. (B) Layers off & on functionality (circle) to showcase gross and intraoperative correlation to highlight the hand-drawn pathological abnormality. (Color version of figure is available online.)

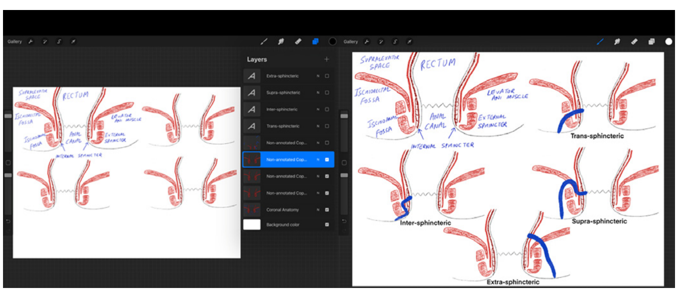

Figure 2. Procreate® copy and pasting: (A) Functionality to copy an anatomical graphic (circle) and paste it across a figure to highlight different pathological processes. (B) Multiple Coronal anal canal graphics copy and pasted in the previous subpart now showing various types of Perianal fistulae (arrows). (Color version of figure is available online.)

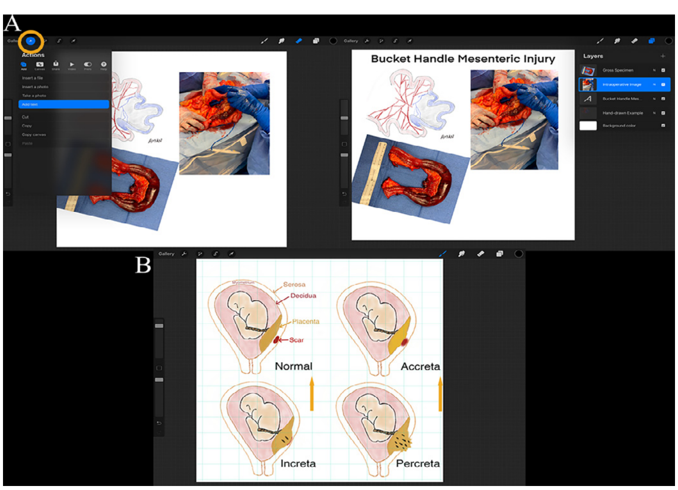

Figure 3. Procreate® add text and drawing guide: (A) Functionality to add crisp text (circle) when creating figure titles and labels. (B) In-built grid pattern can be used as a guide to adjust the positioning of figures and text labels (arrows). (Color version of figure is available online.)

formattable text can be added to any figure (Fig 3A) and by using the grid pattern as a drawing guide, text labels can be carefully adjusted to create publication quality figures (Fig 3B).

Visible Body Human Atlas®

Digital human atlases have pioneered anatomical teaching in the last few decades providing an excellent alternative to cadaveric dissection. Recently this technology is widely available on touch screen devices such as tablets and smartphones where students can rotate anatomical structures in real time using applications such as the Visible Body Human Atlas® app. One such example is to highlight the spatial correlation of celiac ganglion to the peripancreatic vasculature to teach its involvement in pancreatic cancer especially when the student can rotate the 3D rendered model to match the plane used for axial CT examinations (Fig 4). This application even provides side-by-side comparisons of cross-sectional radiological images with 3D rendered models of abdominal anatomy which are essential for first year radiology resident and medical student education (Fig 5). Different anatomical structures

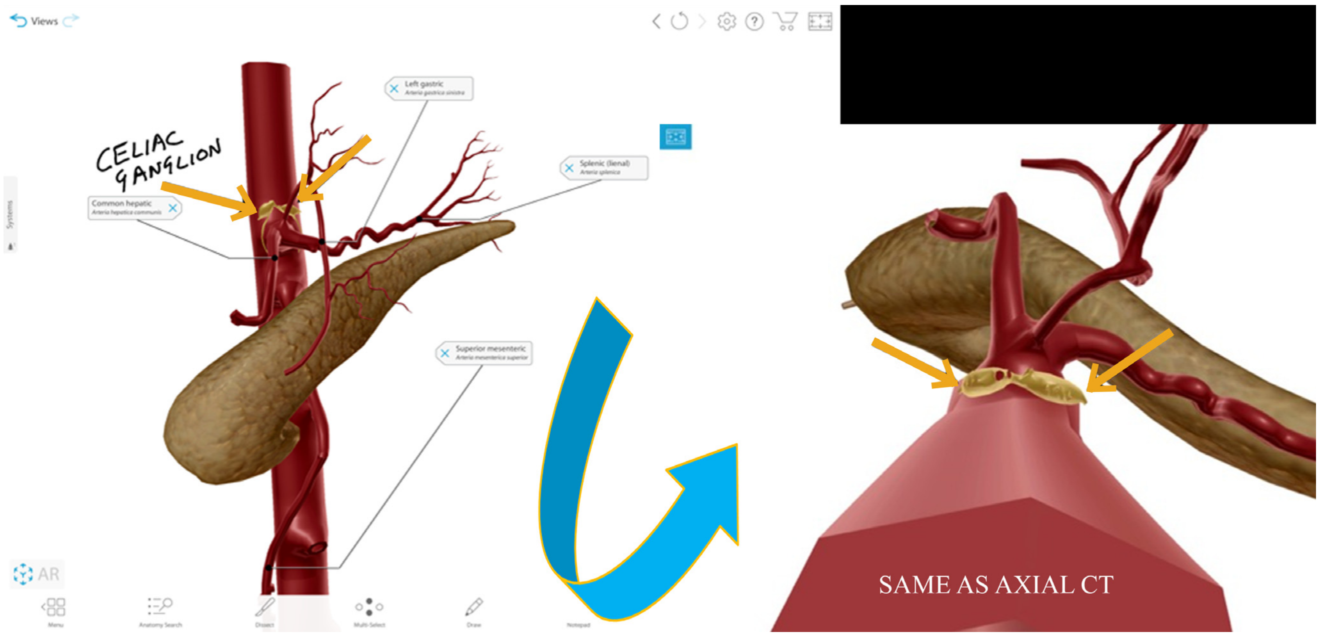

Figure 4. Visible Body Human Atlas® 3D rotation: Screenshot demonstrating 3D correlation of celiac ganglion (arrows) to adjacent anatomical structures with ability to rotate this three dimensional anatomy to match an axial CT scan for better understanding of celiac ganglion's correlation to the peripancreatic vasculature. (Color version of figure is available online.)

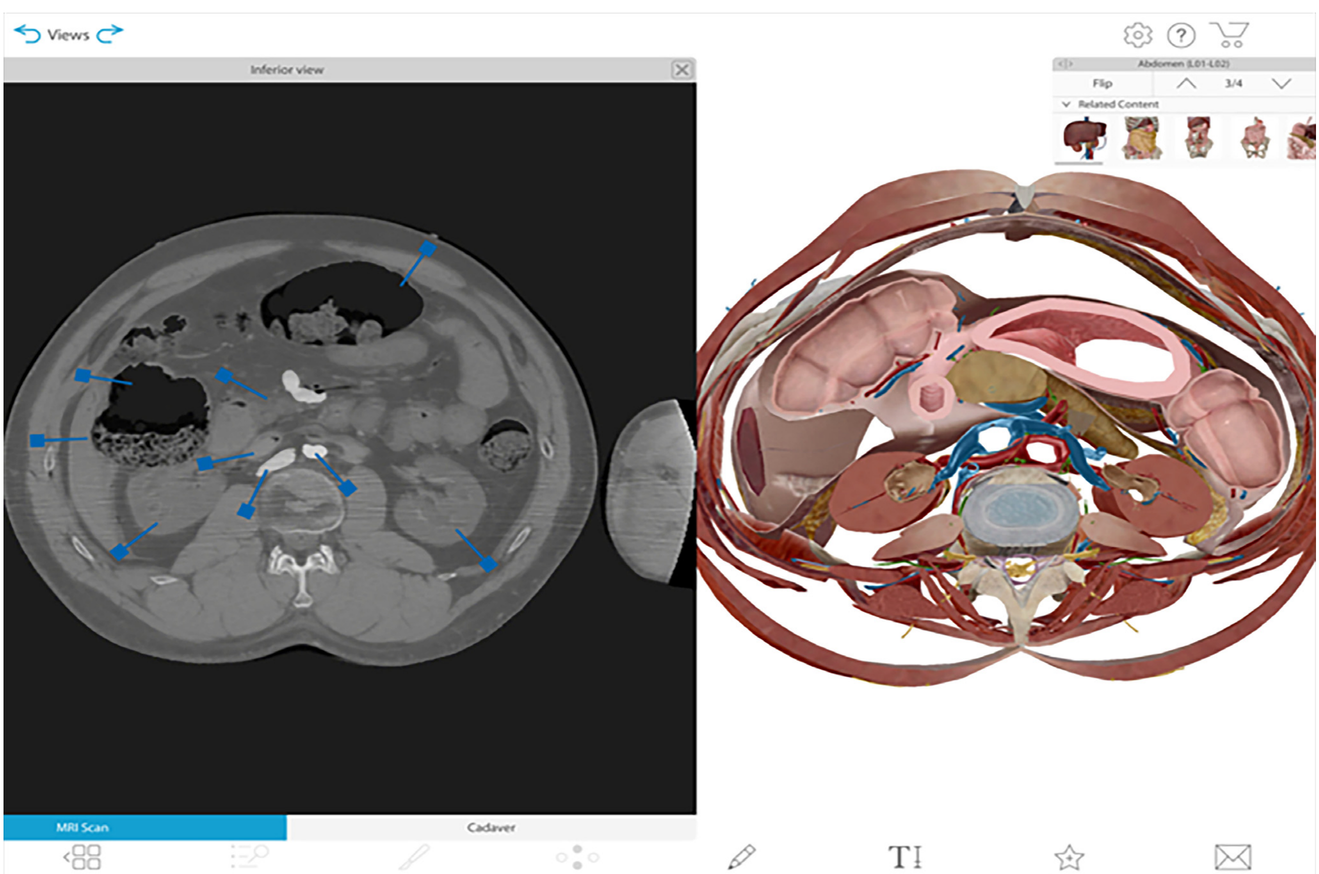

Figure 5. Visible Body Human Atlas® cross sectional correlation: Functionality to make cross sectional radiological image comparisons with a 3D rendered model of abdominal anatomy at similar levels for a more comprehensive anatomical-radiologic correlation. (Color version of figure is available online.)

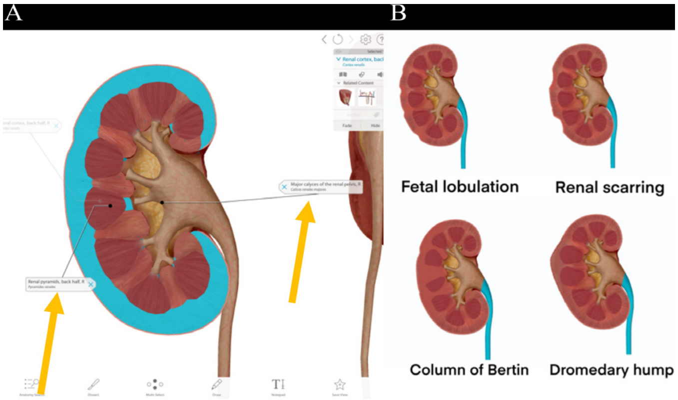

Figure 6. Visible Body Human Atlas® tag and export function: (A) Ability to add or delete anatomical structures with appropriate tags (arrows) in a 3D rendered model. (B) Anatomical graphics from Visible Body Human Atlas® can be exported to applications like Procreate® to create and showcase different anatomical variants. (Color version of figure is available online.)

within the same organ or anatomical region can be added to the 3D rendered model which are then highlighted with tags for the best teaching experience (Fig 6A). Lastly, graphics created in this app can be exported to drawing apps such as Procreate® (highlighted previously) to create different normal variants for the purposes of teaching and showcasing subtle anatomical differences (Fig 6B).

CONCLUSION

Radiology teaching needs to adapt to the constantly evolving digital era through the usage of microlearning and innovative tablet apps and tools. These learning and teaching strategies are not new but accentuated due to safety concerns of COVID-19 pandemic. Some potential next-steps institutions can take include helping faculty understand these methods, designating champions within the staff to facilitate adoption and adaptation, and by monitoring student satisfaction and performance. The barriers to adoption of these learning styles are mainly focused upon the time commitment needed to transition modalities and the monetary funds needed for product support. Schools can use these methods to augment the teaching of their digital curricula in order the preserve the educational yield on par with levels of their original models by utilizing microlearning strategies to maintain the amount of active learning. This will be key in maintaining essential medical teaching in the currently trying socially and physically distant times of COVID-19 as well as in similar future scenarios.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

ACKNOWLEDGMENTS

We would like to thank Dr. Aya Kamaya (Professor, Body Imaging, Stanford University) for her feedback regarding the manuscript content and figures.

REFERENCES

1. Atta IS, AlQahtani FN. Matching medical student achievement to learning objectives and outcomes: a paradigm shift for an implemented teaching module. Adv Med Educ Pract 2018; 9:227–233.
2. DeWitt RD. Planning for active learning in the didactic classroom. J Physician Assist Educ 2019; 30:41–46.
3. Irby DM, Cooke M, O'Brien BC. Calls for reform of medical education by the Carnegie Foundation for the Advancement of Teaching: 1910 and 2010. Acad Med 2010; 85:220–227.
4. Skochelak SE, Stack SJ. Creating the medical schools of the future. Acad Med 2017; 92:16–19.
5. Sinnayah P, Rathner JA, Loton D, et al. A combination of active learning strategies improves student academic outcomes in first-year paramedic bioscience. Adv Physiol Educ 2019; 43:233–240.
6. Redmond CE, Healy GM, Fleming H, et al. The integration of active learning teaching strategies into a radiology rotation for medical students improves radiological interpretation skills and attitudes toward radiology. Curr Probl Diagn Radiol 2020; 49:386–391.
7. Roberts D. Higher education lectures: from passive to active learning via imagery? SAGE 2017; 20:63–77.
8. Schmidt HG, Cohen-Schotanus J, Arends LR. Impact of problem-based, active learning on graduation rates for 10 generations of Dutch medical students. Med Educ 2009; 43:211–218.
9. Pinto A, Brunese L, Pinto F, et al. E-learning and education in radiology. Eur J Radiol 2011; 78:368–371.
10. Worm BS. Learning from simple ebooks, online cases or classroom teaching when acquiring complex knowledge. A randomized controlled trial in respiratory physiology and pulmonology. PLoS One 2013; 8: e73336.
11. Ruiz JG, Mintzer MJ, Leipzig RM. The impact of E-learning in medical education. Acad Med 2006; 81:207–212.
12. De Gagne JC, Park HK, Hall K, et al. Microlearning in health professions education: scoping review. JMIR Med Educ 2019; 5:e13997.
13. Wijesooriya NR, Mishra V, Brand PLP, et al. COVID-19 and telehealth, education, and research adaptations. Paediatr Respir Rev 2020; 35:38–42.
14. Chertoff JD, Zarzour JG, Morgan DE, et al. The early influence and effects of the coronavirus disease 2019 (COVID-19) pandemic on resident education and adaptations. J Am Coll Radiol 2020; 17:1322–1328.
15. Gaur U, Majumder MAA, Sa B, et al. Challenges and opportunities of preclinical medical education: COVID-19 crisis and beyond. SN Compr Clin Med 2020: 1–6.
16. Sundaram KM, Pevzner SJ, Magarik M, et al. Preliminary evaluation of gamification in residency training. J Am Coll Radiol 2019; 16(9 Pt A):1201–1205.
17. Murdock HM, Penner JC, Le S, et al. Virtual morning report during COVID-19: a novel model for case-based teaching conferences. Med Educ 2020; 54:851–852.
18. Kraut AS, Omron R, Caretta-Weyer H, et al. The flipped classroom: a critical appraisal. West J Emerg Med 2019; 20:527–536.
19. Shail MS. Using micro-learning on mobile applications to increase knowledge retention and work performance: a review of literature. Cureus 2019; 11:e5307.

20. MacLeod S, Reynolds MG, Lehmann H. The mitigating effect of repeated memory reactivations on forgetting. NPJ Sci Learn 2018; 3:9.
21. Dolasinski MJ, Reynolds J. Microlearning: a new learning model. J Hosp Tour Res 2020; 44:551–561.
22. Yasung Park YK. A design and development of micro-learning content in e-Learning system. Int J Adv Sci Eng Inf 2018; 8:56–61.
23. Sirwan Mohammed G, Wakil K, Sirwan Nawroly S. The effectiveness of microlearning to improve students' learning ability. Int J Educ Res Rev 2018; 3:32–38.
24. Rengier F, Hafner MF, Unterhinninghofen R, et al. Integration of interactive three-dimensional image post-processing software into undergraduate radiology education effectively improves diagnostic skills and visual-spatial ability. Eur J Radiol 2013; 82:1366–1371.
25. Bedford J, Enria D, Giesecke J, et al. COVID-19: towards controlling of a pandemic. Lancet 2020; 395:1015–1018.
26. COVID-19 impact on education. 2020; Available at: https://en.unesco.org/covid19/educationresponse.
27. Sahu P. Closure of universities due to coronavirus disease 2019 (COVID-19): impact on education and mental health of students and academic staff. Cureus 2020; 12:e7541.
28. Dedeilia A, Sotiropoulos MG, Hanrahan JG, et al. Medical and surgical education challenges and innovations in the COVID-19 era: a systematic review. In Vivo 2020; 34(3 suppl):1603–1611.
29. Darras KE, Spouge RJ, de Bruin ABH, et al. Undergraduate radiology education during the COVID-19 pandemic: a review of teaching and learning strategies. Can Assoc Radiol J 2020; 72(2):194–200.
30. Recht MP, Fefferman NR, Bittman ME, et al. Preserving radiology resident education during the COVID-19 pandemic: the simulated daily readout. Acad Radiol 2020; 27:1154–1161.
31. Robbins JB, England E, Patel MD, et al. COVID-19 impact on well-being and education in radiology residencies: a survey of the association of program directors in radiology. Acad Radiol 2020; 27:1162–1172.
32. DePietro DM, Santucci SE, Harrison NE, et al. Medical student education during the COVID-19 pandemic: initial experiences implementing a virtual interventional radiology elective course. Acad Radiol 2021; 28:128–135.
33. Greenhalgh T. Computer assisted learning in undergraduate medical education. BMJ 2001; 322:40–44.
34. Peska DN, Lewis KO. Uniform instruction using web-based, asynchronous technology in a geographically distributed clinical clerkship: analysis of osteopathic medical student participation and satisfaction. J Am Osteopath Assoc 2010; 110:135–142.
35. Maleck M, Fischer MR, Kammer B, et al. Do computers teach better? A media comparison study for case-based teaching in radiology. Radiographics 2001; 21:1025–1032.
36. McRoy C, Patel L, Gaddam DS, et al. Radiology education in the time of COVID-19: a novel distance learning workstation experience for residents. Acad Radiol 2020; 27:1467–1474.
37. Li CH, Rajamohan AG, Acharya PT, et al. Virtual read-out: radiology education for the 21st century during the COVID-19 pandemic. Acad Radiol 2020; 27:872–881.
38. Kalludi S, Punja D, Rao R, et al. Is video podcast supplementation as a learning aid beneficial to dental students? J Clin Diagn Res 2015; 9: Cc04–Cc07.
39. Rose S. Medical student education in the time of COVID-19. JAMA 2020; 323:2131–2132.
40. Bonwell CC, Eison JA. Active learning : creating excitement in the classroom. Washington, D.C: School of Education and Human Development, George Washington University, 1991.
41. Chick RC, Clifton GT, Peace KM, et al. Using technology to maintain the education of residents during the COVID-19 pandemic. J Surg Educ 2020; 77:729–732.
42. Gabr AM, Li N, Schenning RC, et al. Diagnostic and interventional radiology case volume and education in the age of pandemics: impact analysis and potential future directions. Acad Radiol 2020; 27:1481–1488.
43. Kogan M, Klein S, Hannon CP, et al. Orthopaedic education during the COVID-19 pandemic. J Am Acad Orthop Surg 2020; 28:e456–e464.
44. Thistlethwaite JE, Davies D, Ekeocha S, et al. The effectiveness of case-based learning in health professional education. A BEME systematic review: BEME Guide No. 23. Med Teach 2012; 34:e421–e444.
45. Deterding S, Kaled R, Nacke L, et al., Gamification: toward a definition. 2011. 12-15.
46. Dichev C, Dicheva D. Gamifying education: what is known, what is believed and what remains uncertain: a critical review. Int J Educ Technol High Educ 2017; 14:9.
47. Rutledge C, Walsh CM, Swinger N, et al. Gamification in action: theoretical and practical considerations for medical educators. Acad Med 2018; 93:1014–1020.
48. Bharamgoudar R. Gamification. Clin Teach 2018; 15:268–269.
49. (FLN), F.L.N. The four pillars of F-L-I-P^{TM} 2014; Available at: www.flippedlearning.org/definition.
50. Sivarajah RT, Curci NE, Johnson EM, et al. A review of innovative teaching methods. Acad Radiol 2019; 26:101–113.
51. Chen F, Lui AM, Martinelli SM. A systematic review of the effectiveness of flipped classrooms in medical education. Med Educ 2017; 51:585–597.
52. Young JQ, Van Merrienboer J, Durning S, et al. Cognitive load theory: implications for medical education: AMEE guide no. 86. Med Teach 2014; 36:371–384.
53. Bledsoe S, Harmeyer D, Wu F, et al. Utilizing Twitter and #Hashtags Toward Enhancing Student Learning in an Online Course Environment. Int. J. Distance Educ. Technol. 2014; 12:75–83.
54. Diug B, Kendal E, Ilic D. Evaluating the use of twitter as a tool to increase engagement in medical education. Educ Health (Abingdon) 2016; 29:223–230.
55. Bannister J, Neve M, Kolanko C. Increased educational reach through a microlearning approach: can higher participation translate to improved outcomes? J Eur CME 2020; 9:1834761.
56. Freed PE, Bertram JE, McLaughlin DE. Using lecture capture: a qualitative study of nursing faculty's experience. Nurse Educ Today 2014; 34:598–602.
57. Narula N, Ahmed L, Rudkowski J. An evaluation of the '5 Minute Medicine' video podcast series compared to conventional medical resources for the internal medicine clerkship. Med Teach 2012; 34: e751–e755.
58. Wang T, Wang F, Shi L. The use of microblog-based case studies in a pharmacotherapy introduction class in China. BMC Med Educ 2013; 13:120.
59. Chuang Y-H, Tsao C-W. Enhancing nursing students' medication knowledge: the effect of learning materials delivered by short message service. Comput Educ 2013; 61:168–175.
60. Cheng YT, Liu DR, Wang VJ. Teaching splinting techniques using a just-in-time training instructional video. Pediatr Emerg Care 2017; 33:166–170.
61. Evans DJ. Using embryology screencasts: a useful addition to the student learning experience? Anat Sci Educ 2011; 4:57–63.
62. Guo D, McTigue EM, Matthews SD, et al. The impact of visual displays on learning across the disciplines: a systematic review. Educ Psychol Rev 2020; 32:627–656.
63. Vieira C, Parsons P, Byrd V. Visual learning analytics of educational data: a systematic literature review and research agenda. Comput Educ 2018; 122:119–135.
64. Paivio A, Csapo K. Picture superiority in free recall: imagery or dual coding? Cognit Psychol 1973; 5:176–206.
65. Lipton ML, Lipton LG. Enhancing the radiology learning experience with electronic whiteboard technology. AJR Am J Roentgenol 2010; 194:1547–1551.
66. Alsaid B. Slide shows vs graphic tablet live drawing for anatomy teaching. Morphologie 2016; 100:210–215.
67. Wammes JD, Meade ME, Fernandes MA. Learning terms and definitions: drawing and the role of elaborative encoding. Acta Psychol (Amst) 2017; 179:104–113.
68. Havens KL, Saulovich NA, Saric KJ. A case report about anatomy applications for a physical therapy hybrid online curriculum. J Med Libr Assoc 2020; 108:295–303.