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From Chalkboard, Slides, and Paper to e-Learning: How Computing Technologies Have Transformed Anatomical Sciences Education

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Until the late-twentieth century, primary anatomical sciences education was relatively unenhanced by advanced technology and dependent on the mainstays of printed textbooks, chalkboard- and photographic projection-based classroom lectures, and cadaver dissection laboratories. But over the past three decades, diffusion of innovations in computer technology transformed the practices of anatomical education and research, along with other aspects of work and daily life. Increasing adoption of first-generation personal computers (PCs) in the 1980s paved the way for the first practical educational applications, and visionary anatomists foresaw the usefulness of computers for teaching. While early computers lacked high-resolution graphics capabilities and interactive user interfaces, applications with video discs demonstrated the practicality of programming digital multimedia linking descriptive text with anatomical imaging. Desktop publishing established that computers could be used for producing enhanced lecture notes, and commercial presentation software made it possible to give lectures using anatomical and medical imaging, as well as animations. Concurrently, computer processing supported the deployment of medical imaging modalities, including computed tomography, magnetic resonance imaging, and ultrasound, that were subsequently integrated into anatomy instruction. Following its public birth in the mid-1990s, the World Wide Web became the ubiquitous multimedia networking technology underlying the conduct of contemporary education and research. Digital video, structural simulations, and mobile devices have been more recently applied to education. Progressive implementation of computer-based learning methods interacted with waves of ongoing curricular change, and such technologies have been deemed crucial for continuing medical education reforms, providing new challenges and opportunities for anatomical sciences educators. Anat Sci Educ 9: 583–602. © 2016 American Association of Anatomists.

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INTRODUCTION

The past three decades have seen remarkable, evolutionary changes taking place in the way anatomical sciences and health sciences have been taught and learned. Perhaps most the most fundamentally influential educational technology factor in all of these changes has been the rise of the integrated circuit digital computer and its integration into a vast range of devices and instruments (Campbell-Kelly and Aspray, 2003; Swedin and Ferro, 2007), from the now-ubiquitous personal computers (PCs) to medical imaging systems to smartphones, tablets, and other mobile devices. Use

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of PCs and more recent mobile computing devices has become an integral part of learning and everyday life for students and faculty, also including a range of common appliances, tools, and clinical services that less visibly depend on embedded computer technology.

In the mid- and late-twentieth century, anatomical sciences education in Western medical schools was typically characterized by assigned textbook readings and lectures variably accompanied by chalkboard diagrams and projected photographic slides, from which students could make their own handwritten notes. Each hour of lecture topic was variably associated with hours of active learning laboratory exercises: regional cadaver dissections for gross anatomy, microscope slides studies of cells and tissues for microscopic anatomy, and nervous system slides, preserved specimens, and brain dissections for neuroanatomy (Collins et al., 1994; Hightower et al., 1999; Drake et al., 2002; Heylings, 2002; Blake et al., 2003; Hildebrandt, 2010).

This "status quo" was progressively and gradually changing concurrently with the rise of educational computing in the anatomical and health sciences, beginning in the early days of the "mainframe" computer and the first experiments in "computer-aided instruction," through early multimedia-based "computer-assisted learning," to currently pervasive "*e-learning*" (electronic learning) with Web-based online learning resources, social networking, and multimedia on student laptops and other mobile devices. This diffusion of innovations in learning technologies over the last three decades also occurred concurrently with the decline of free-standing, research-based anatomy departments and graduate programs at major universities, along with reductions in anatomical science education curricular hours accompanying waves of medical education curricular reform (Drake et al., 2002, 2009; Papa and Vaccarezza, 2013; Drake et al., 2014). And while the lattermost programmatic changes have been largely rationalized by principles of adult learning and humanistic clinical practices, e-learning methods have become practical tools and integral means for implementing and supporting new curricula.

Anatomists have played vital roles in introducing and promoting many of these computer-based educational innovations, along with defining important visions for the future of instructional technologies within health sciences education (e.g., Walsh and Bohn, 1990; Rosse, 1995; Spitzer and Whitlock, 1998; McNulty et al., 2000; Sugand et al., 2010). To a large degree then, their successful establishment of new integrated anatomical e-learning methods has been instrumental in the ongoing success and continuity of rapidly evolving multidisciplinary health sciences education. In fact, recent United States and Canadian consensus reports prescribing further medical education reforms have focused on the important roles of new technologies in achieving the newest recommended clinical practice and educational changes (Skochelak, 2010).

The purpose of this review is to provide historical perspectives on the important technological innovations and resulting computer-based learning applications that have shaped anatomical sciences education as we currently know it. Published evidence will also be reviewed for the introduction and educational effectiveness of exemplary specific learning resource innovations. The overall account will be initially framed in the context of socio-behavioral research-based diffusion of innovations (DOI) theory (Rogers, 2003), which provides useful practical insights into principles, factors, and time-course for the success or failure of new technology implementations, applicable to learning resources as well as to new curricula.

These principles will remain important in the future: Because effective e-learning is not that old globally, having appeared and evolved rapidly during the careers of senior anatomists, it will continue to evolve significantly with newer technologies and curricula (Friederichs et al., 2014; Masic et al., 2014; Cook et al., 2015; Fletcher et al., 2015). A persuasive call has also gone out for making appropriate use of e-learning methods with other active methods of comprehensive structural learning, in modernizing anatomical education for newer integrated curricula aimed at training competent healthcare professionals (Sugand et al., 2010; Skochelak, 2010). And as will be illustrated in this review, earlier innovations beget later new inventions and uses, so understanding the foundations of existing technologies may facilitate the development of useful new applications, resources, and methods for learning.

DIFFUSION OF INNOVATIONS 101: SOCIAL PROCESSES IN ADOPTION OF NEW TECHNOLOGIES

As originally formally defined by Rogers (1962, 2003), diffusion is the complex process by which acceptance of an innovation is communicated to members of a social system over a period of time, via specific channels (Mahajan and Peterson, 1985). The four highest level variables operating in the diffusion process are the characteristics of the innovation itself, communications channels, social systems, and time. The principles of diffusion of innovations apply not only to processes of adopting new hardware technologies but also to dissemination of new practices (e.g., problem-based learning and healthcare; Greenhalgh et al., 2005), ideas, philosophies, and ways of thinking (e.g., about "cognitive load" of multimedia). The following brief review of the essentials of diffusion of innovations frames and provides usable context for anatomists who want to understand important factors involved in the ongoing acceptance and integration of new computing technologies, software applications, and learning practices (for additional discussion, see Trelease, 2006b). See Figure 1 for a graphic summary integrating the most important elements of diffusion of innovations, including a depiction of innovation adoption curves (bottom cell, right column).

Innovations need not be absolutely or objectively new, although they may be perceived as new by individual adopters at given times. Thus, we will see that some innovations may take many years and redevelopment of desirable features, software, or learning practices in order to achieve popular acceptance and mass adoption in new contexts (e.g., the first development of tablet computers in the 1990s and their widespread public acceptance only after 2010).

"Innovation" and "new technology" are frequently considered synonyms, and one can further distinguish hardware and software aspects of innovations. Although the hardware aspects of a new technology may be apparent, the social aspects and practical consequences of its software design and usage are typically much less obvious. Potential adopters of an innovation need persuasive information about the new technology in order to be convinced that adopting it will have positive consequences for them. Communications of factual information about an innovation's characteristics are

Factors Affecting Diffusion	Sub-factors Affecting Diffusion	Relationships to Diffusion
Information about innovation	• **software information**: needed for user to understand desired functionality • **evaluation information**: needed for reducing user uncertainty about the expected consequences of adoption	Optimal software and evaluation information facilitate adoption decision-making
Innovation characteristics	• **relative advantage:** perceived degree to which an innovation is superior to what it supercedes • **compatibility:** perceived degree to which an innovation is consistent with adopters' needs, values, and personal experiences • **complexity:** degree to which an innovation seems difficult to understand and to use • **trialability:** degree to which a user can experiment temporarily with an innovation • **observability:** degree to which others can see the results of an innovation	Useful software and evaluation information items that facilitate individual adoption decision-making and diffusion: High relative advantage, compatability, trialability, and observability can speed adoption; perceived complexity can be a diffusion barrier
Communications	• **communications:** processes by which people share information about new ideas • **communications channels:** specific means by which information is shared between innovators and potential adopters	Good use of word-of-mouth and Web channels can share information that facilitates adoption and speeds diffusion
Social system parameters	• **social structure:** adopter population may be more *heterophilic* (varied) or *homophilic* (uniform) in relation to certain individual characteristics • **system norms:** established behavior patterns that define a range of tolerable behaviors or standards for members of a social system • **opinion leaders and change agents:** facilitators of adoption and diffusion • **types of innovation-decisions supported:** collective (consensus), optional (individual), or authority-based (e.g., by educational or administrative fiat) • **consequences of adoption:** desirable vs. undesirable, direct vs. indirect	Social system defined as an interrelated group of individuals, informal groups, organizations, or others engaged in common activities or shared work toward a common goal; facilitators are most persuasive, positive communicators
Individual adopter characteristics	• **INnovators:** earliest adopters, may not be best facilitators (seen as "techies") • **Early Adopters:** contribute to the inflection point of sigmoid diffusion curve • **Early Majority:** contribute to the rising phase of sigmoid diffusion curve • **Late Majority:** contribute to the end-rising phase of sigmoid diffusion curve • **LAggards:** contribute to the shoulder of sigmoid diffusion curve	
Time	• variable, as required for the individual innovation-decision process • classifier, for adopting individuals (above) • variable, for rate of innovation adoption in a population	

Figure 1.

Crucial factors, variables, and relationship affecting the diffusion of innovations. For the diffusion curves illustration embedded in the right-bottom cell, note that the X-axis (elapsed time) abbreviations are explained by the left-adjoining center column cell listing Individual Adopter types. For the Y-axis, N indicates number of individuals adopting a given innovation.

thus crucial in facilitating adoption decision making, and depending on the social system (e.g., first year medical students), early adopters (i.e., "techies") may not be the best communicators of a new technology's desirability and usefulness. The overall rate of adoption in a population is a complex function of the combined interactions of the nature of the innovation, its innovativeness, diffusion communications, and the social system, and this is most often depicted as a sigmoid distribution curve of adoptions over time (see Fig. 1). For example, this can be seen in data on U.S. and global adoption of smartphones and tablets (Rainie and Poushter, 2014; Zickuhr and Rainie, 2014).

A few additional aspects of diffusion of innovations are relevant to adoption decision making (Rogers, 2003), particularly in an educational environment. Adoption decisions may be consensus-based, such as mass public adoptions of smartphones, and these may also emerge from evidence-based, democratic governance methods (e.g., faculty voting for curricular change). Alternatively, decisions may be authority-based, such as when an administration or executive committee decides to change a curriculum without polling the faculty at large.

In practical terms, the anatomical sciences literature has born witness to the application of many innovations over the past centuries, frequently serving to further facilitate their diffusion. For example, the publication of Andreas Vesalius' *De Humani Corporis Fabrica Libri Septem* (Vesalius, 1543) had a historically acknowledged role in facilitating the more widespread acceptance of learning by human dissection (O'Malley, 1964). In publishing journal articles and books on new educational applications of technology, anatomists have thus played essential and continuing roles in early adoption of a variety of innovations and in facilitation of their diffusion.

From the late twentieth century through the present day, the greatest innovations have resulted from the application of digital computer technologies that have not only transformed the activities of daily life, but also the practices of science, medicine, and surgery. As we shall review in the following sections, successive innovations in personal computing hardware and software, the development of the Internet and the World Wide Web, and medical imaging modalities have provided the most significant major tools and methods crucial to present day technology-enhanced clinically oriented anatomical sciences education. Other innovations in video, simulations, and new computing platforms have built on earlier technologies for other synergistic learning enhancements.

A conceptual diagram of the complex relationships between these innovations is shown in Figure 2. In the left column, readers will find the primary innovations that will be covered in the following major sections, such as the digital

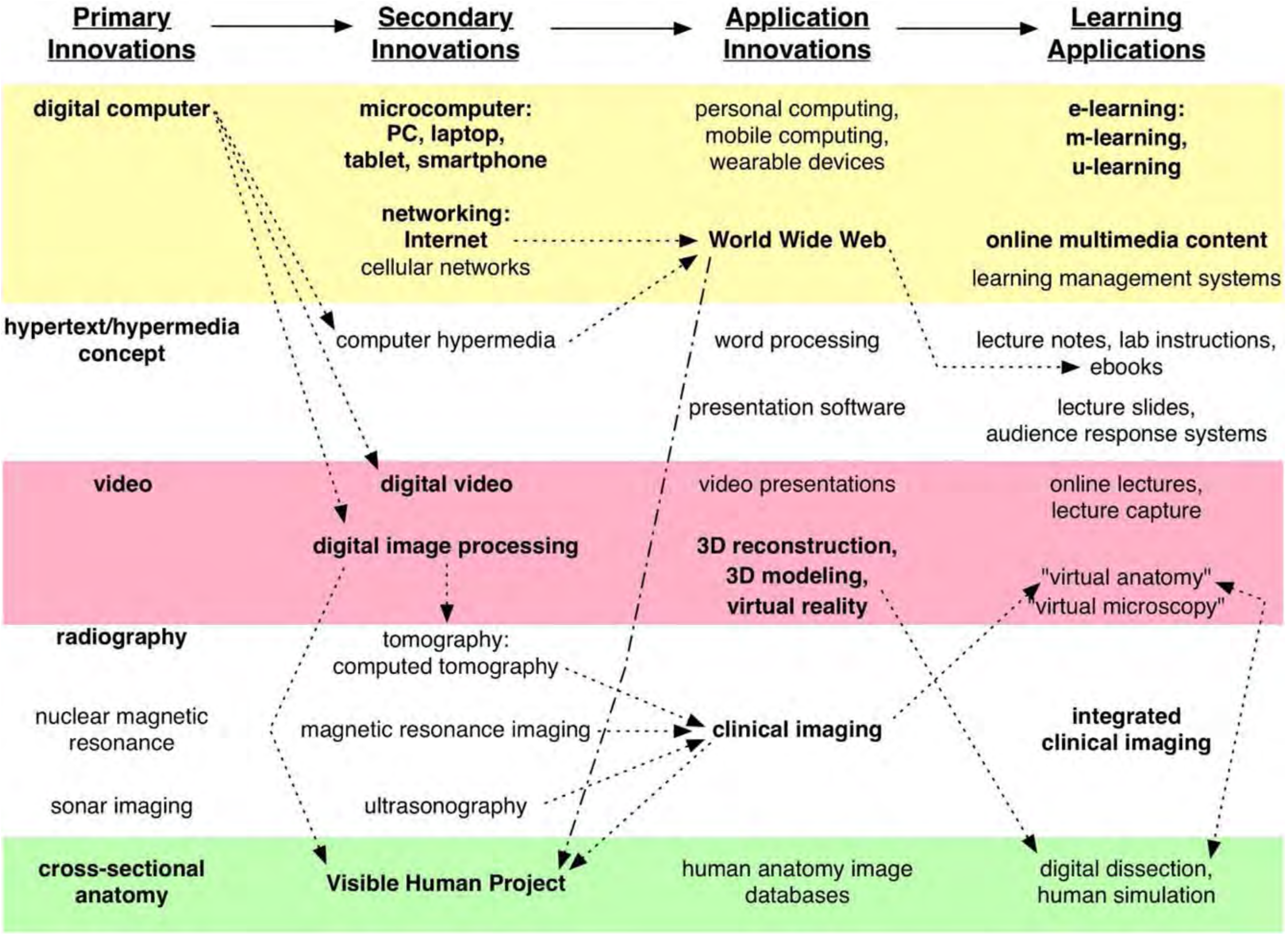

Figure 2.

Concept map diagram of important primary and secondary innovations and their relationships to learning enhancement applications in anatomical sciences education.

computer, hypertext/hypermedia, video, radiography, et cetera. The next two columns map secondary and application innovations that will be discussed in section text, such as the personal computer and mobile computing, respectively, for digital computers. Finally, in the right-most column are mapped learning application innovations, such as e-learning and m-learning with digital computers. Figure 2 also includes vector lines depicting the some of the most important 'vertical' interrelationships between primary, secondary, and application innovations and their learning applications.

Of these core computer-based innovations, the Web has had the deepest and the most broad-based influences, serving as a common, integrating multimedia framework and pervasive universal distribution medium that has been applied to all aspects of life and contemporary education, including gross, microscopic, and neurological anatomy and embryology. And while each anatomical sub-discipline has had its own specific combination of needs for development of crucial and effective tools (i.e., high resolution macroscopic and three-dimensional digital imaging for gross, large scale microscopic image management for histology, macroscopic, microscopic, and clinical image processing for neuroanatomy, etc.), the following overview will focus on the development of the most important shared innovations applied to anatomical sciences education, along with sub-discipline-specific examples. Finally, these core computer-based and e-learning technologies and methods also apply broadly to the successful overall delivery, management, and continuing evolution of contemporary health sciences education and multidisciplinary curricula at institutional and global levels.

THE FIRST WAVES: COMPUTER-ASSISTED INSTRUCTION AND EARLY EDUCATIONAL EFFORTS

The first concentrated efforts at putting digital computers to work in education commenced in the 1960s, when the massive, multi-cabinet "mainframe" system was the primary computer platform. Because mainframes were expensive, large, and required special-purpose, air conditioned facilities, early educational computing projects and research operated out of a relatively small number of well-funded universities. These earliest efforts were first referred to as "computer-assisted instruction" (CAI; Larkin and Chabay, 1995), and given the existing technology's computational and limited display capabilities, they focused most productively on automating text-based approaches to mathematics and language instruction in primary and secondary schools (Suppes and Morninstar, 1969).

These early studies, whether they were labeled CAI, computer-based instruction/learning (CBI/CBL) or computer-aided learning, demonstrated some success in facilitating text-based student learning of numerical and linguistic principles and content almost entirely on-machine, but they were also criticized and viewed as of limited utility and practicality. At this time, there were no significant applications of CAI to contemporary anatomical learning, which was as much dependent on visual imagery as on text-based conceptual descriptions and relationships (i.e., in photographic lecture slides, chalkboard diagrams, textbooks, and notes). In retrospect, it has been observed that success of early computer learning methodology was limited by the cost and special infrastructure needed to disseminate from mainframe computers to remote school sites. And by the 1980s, CAI was still largely viewed as a research subject rather than as an accepted learning tool. But remarkably, the legacy phrase "computer-assisted instruction" and related variant terms for computer-enhanced learning have endured, being cited in a variety of anatomical and health sciences education papers through the 1990s and into the early 21st century (Pradhan and Dev, 1993; Toth-Cohen, 1995; Lambert et al., 1997; Nieder et al., 2000; McNulty et al., 2004; Cod and Choudhury, 2011).

THE RISE OF PERSONAL COMPUTING AND ITS EDUCATIONAL APPLICATIONS

The 1980s brought a major computing innovation and modern cultural paradigm shift away from mainframes, with the introduction of the first generation of compact and affordable integrated circuit microcomputer-based PCs that could be used as "information appliances" at home and in classrooms. For a number of reasons, however, diffusion of new desktop PCs into classrooms and homes proceeded slowly for over a decade. Useful commodity and instructional software required custom-programming, thorough assessment, and proof of educational value before schools and families would commit significant funds for mass adoption. Furthermore, these early PCs had very primitive graphics displays, virtually excluding the use of video or photographic images, such as those now integrated into contemporary gross and microscopic anatomy lectures and laboratories.

The earliest anatomy teaching applications focused on computer based enhancements of more conventionally organized text-based information such as lecture notes (Russell et al., 1986) and atlas-like compendia. When it became possible to interface and to drive optical videodisc and later CD-ROM (Compact Disc Read-Only Memory) with PCs, the first early multimedia learning applications were developed (Frisbie, 1993; Gest and VanBiervliet, 1994; Downing, 1995; Kim et al., 1995; Myers et al., 1995; Pawlina and Olson, 1996; Gosling et al., 1997). Excellent examples of this early approach to multimedia learning were seen with the Slice of Life videodiscs, large-scale, indexed collections of video-resolution anatomical and histological images that were used by academic developers for dual-monitor structural displays alongside dedicated text-based instructional programs (Stensaas, 1993; Webber et al., 1995). The Vesalius Project at Colorado State University and the Human Dissection Project at the University of Florida represented early efforts that used videodiscs to create an interactive anatomy atlas (McCracken and Spurgeon, 1991) and interactive manual for human dissection (Rarey et al., 1995).

The first substantial use of computers in regular anatomy instruction emerged in the 1990s, with improvements in PC color graphics and interactive user interfaces for operating systems like Microsoft Windows 3.1 and Apple Macintosh operating system (OS). Perhaps the biggest single early software advance was the release of the PowerPoint presentation program with the mass-market Microsoft Windows 3.0 operating system and Microsoft Office software suite in 1990, which made it possible to give a slide-based lecture with a PC and video projector (n.b., PowerPoint had been originally released as "Presenter" on the Macintosh computers in 1987). Beginning in the mid-1990s, PowerPoint presentations began to replace then-current 35 mm slides and overhead projector transparencies as standard lecture media, with easily composed text pages supporting embedded high-resolution anatomical and histological images, as well as custom animations and attention-focusing slide transitions (Cook, 1998; Carmichael and Pawlina, 2000). Successive improvements in presentation software have supported embedded video and hyperlinking to online media (see below), as well as more recent audience response system (ARS) methods (Alexander et al., 2009; Wait et al., 2009; Hoyt et al., 2010) that effect adult education recommendations for turning transmissive lecture teaching into interactive learning experiences (Nierenberg, 1998).

An early use of a locally networked client-server structural database for teaching anatomy was the Digital Anatomist Browser at the University of Washington (Brinkley et al., 1993). Macintosh client computers provided students with in-laboratory access to a wide range of anatomical data, images and animation stored on a central server. The Digital Anatomist project presaged the use of the World Wide Web for distance learning (Dailey et al., 1994) and involved its developers in the National Library of Medicine's proposal competition for the Visible Human Project (see following sections).

HYPERTEXT, HYPERMEDIA, AND THE BIRTH OF THE WORLD WIDE WEB

In addition to the progressive improvements in PC graphics and displays in the later 1980s and early 1990s, the growth of the global Internet supported direct information exchange between networked computers and set the stage for the next big transformative innovation: the World Wide Web. Greatly expanding individual PCs' capacity for widely and easily sharing information, the Web integrated earlier concepts of "hypertext" and "hypermedia" to give users "point and click" interactive access to linked and indexed text and high-resolution multimedia files on networked server computers in initially scientific and academic settings.

During the 1930s, American engineer Vannevar Bush originated the idea of a machine ("memex") for managing associatively linked textual information and images, supporting "wholly new forms of encyclopedias" (Bush, 1945). Although his memex was never produced in the pre-digital computer era, Bush's ideas stimulated later inventors, like Theodor Holm "Ted" Nelson, an American pioneer of information technology who developed a computer system model using associatively linked content that he first called "hypertext" and hypermedia" (Nelson, 1965). Working independently on his own NLS hypertext system at Stanford Research Institute, Douglas Carl Englebart, an American engineer and Internet pioneer demonstrated a "hypertext" editing interface to the public for the first time, in what was effectively the birth of the first word processor (Tweney, 2008).

In 1980, English computer scientist Sir Timothy John Berners-Lee (also known as "TimBL") created an early hypertext database system somewhat comparable to a present day "Wiki" or "Wikipedia". In 1989, Berners-Lee proposed and later prototyped a new hypertext project for an Internet-linked server information-sharing facility to be used by physicists working at the European Center for Nuclear Research and other academic institutions: He called it the "World Wide Web" (Berners-Lee and Calliau, 1989). The 'Web era' effectively began in 1994, with the first public release of PC-based Web browser software–NCSA Mosaic (Berners-Lee et al., 1994).

Among the first bioscientific applications for the early Web was the organization and distribution of data for the Visible Human Project (Ackerman, 2002; Baatz, 2004) and the Visible Embryo Project (Doyle et al., 1996), supported by the United States National Library of Medicine. Such projects reciprocally influenced the evolution of publicly released and commercial Web browser software, by necessitating the development of "plug-in" software modules to support the display of high-resolution cross-sectional images (Doyle et al., 1996; Williams and Doyle, 1996). Other aspects of the Visible Human Project are covered in a separate section below.

Among the earliest published proposals for medical educational uses of the Web were those of Kruper et al. (1994), McEnery et al. (1995), and Bradley et al. (1995). As previously noted (Bradley et al., 1995; Brinkley et al., 1997), the Digital Anatomist Project was the first to provide extensive anatomical learning resources for networked access in the form of an interactive atlas with extensive three-dimensional (3D) animation and digital video. In addition to the Visible Embryo Project in the United States (Doyle et al., 1996), a consortium of United Kingdom universities soon made their human embryology databases accessible via the Web (Aiton et al., 1996). In an early telemedicine/tele-education application, a collection of temporal bone, laryngeal, skull and sinus sections was made accessible in a Web-based "virtual laboratory" for otolaryngology learning (Alusi et al., 1997).

McNulty et al. (2000) integrated Web server statistics with individual user surveys and examination performance to assess use of Web-based CAI in their human structure course, and their data indicated no correlation between computer literacy and overall CAI utilization levels. Use of course-related CAI corresponded strongly with ongoing course content, indicating curricular effectiveness, although use of tutorials content coincided more with impending in-course examinations. Discrepancies between recorded usage data and student survey reports also put in question the validity of self-reported student survey usage data. This report is particularly notable, because it represents the first large-scale Web-based instruction utilization study performed (in 1998) at the highly computerized facility at Loyola University Stritch School of Medicine, that was designed specifically around Web-based technologies aimed at enhancing independent and group-based learning. In a subsequent report, McNulty et al. (2002) also demonstrated reduced printing of course materials and lowered reproduction costs with Web-based distribution of instructional resources, the first educational evidence for computer media effectively replacing legacy paper content.

It is worth noting that publication of articles concerned with the primary application of Web resources to anatomical sciences education has declined greatly in post-millennial years, in favor of accounts of a variety of newer "second generation" applications and learning methods effectiveness studies that implicitly and explicitly depend on pervasive, prevailing Web usage. Over a decade since its inception, the Web has become the ubiquitous infrastructural technology underlying the conduct of contemporary post-secondary and pre-professional education, and indeed, the functions of daily life in a society increasingly dominated by the use of smartphones and mobile technologies (e.g., banking, commerce, shopping, travel, social networking, etc.).

MEDICAL IMAGING: COMPUTED TOMOGRAPHY, ULTRASOUND, AND MAGNETIC RESONANCE

Modern clinical imaging, as increasingly integrated into anatomical sciences and medical education, has its roots in both legacy cross-sectional anatomy and in the development of radiology. Cross-sectional anatomy has had an ancient and important role in understanding the internal three-dimensional structure of the body. Leonardo da Vinci may be considered the 'father' of cross sectional anatomy, although his unpublished illustrations were only disclosed centuries later (Bay and Bay, 2009). Cross-sectional images were definitively published in Andreas Vesalius' widely distributed *De Humani Corporis Fabrica Libri Septem* (e.g., Quarta Septimi Libri Figura, brain/head section, page 635; Vesalius, 1543). Over the last few centuries, printed representations of cross-sections were commonly used for learning anatomy, along with preserved cadaveric sections (Ghosh, 2015).

In pursuing the production of comparably precise and accurate images of living human anatomy, several lines of research in the early decades of twentieth century contributed to the foundation of the clinical discipline of radiology. Foremost among these historically was the development of X-ray imaging with analog tomography, then ultrasound, followed by computed tomography (CT) and magnetic resonance (MR) imaging. William Hendee's authoritative monograph (Hendee, 1989) comprehensively reviewed research and development contributing to analog tomography, ultrasound, CT, and MR imaging, and we summarize some of the most important of the innovative concepts and technical precedents in the next several paragraphs.

Tomography

Shortly after Wilhelm Röntgen's 1895 discovery of X-rays (Roentgen rays) and fluoroscopy, the first principles of tomography or body section radiography were invented, for producing selective images of structures according to their depth (Littleton and Littleton, 1996). Credit for the first effective tomography patent (1922) has been historically given to French physician Andre-Edmund-Marie Bocage, and between 1921 and 1936, separate research efforts yielded different mechanical approaches to producing such conventional "analog" tomographic machines. These had in common Bocage's elements of a moving X-ray source positioned over the stationary subject, aimed at a moving recording plate (film) below the subject. Structures above and below the focal plane of the X-ray beam were blurred or effaced from the final image, leaving only a planar section of the body in sharp focus (Hendee, 1989).

Advanced analog X-ray tomographs remained in clinical use until the 1980s, when computed tomography supplanted them with more detailed sectional imaging. The first principles of CT were propounded by American neurologist William H. Oldendorf in 1961, based on producing transmission images of a rotating object by irradiation with a stationary gamma source and sensing with a fixed radiation scintillation detector. Separately, a South African American physicist Allan McLeod McCormick developed advanced computational methods for calculating attenuation of radiation doses, leading to cross-sectional projection imaging. Sir Godfrey Newbold Hounsfield, an English electrical engineer, developed the first images of biological specimens with a fixed, collimated X-ray scanner with a motorized lathe bed specimen holder and fixed scintillation detector. This design led to the development of a clinical scanner that first imaged a frontal lobe tumor in 1971. By 1972, 70 patients had been examined with the new CT scanner, with results reported at the Annual Congress of the British Institute of Radiology (Ambrose and Hounsfield, 1973). Subsequent widespread publicity and acclaim led to commercial investment in four successive generations of scanner development (Hendee, 1989; Kalender, 2005).

Hounsfield and McCormick subsequently shared the 1979 Nobel Prize for Physiology or Medicine (Richmond, 2004), and CT was established as the first medical technology to employ a digital computer as an integral component of both data acquisition and analysis. Michael Vannier and colleagues at the Mallinckrodt Institute of Radiology in Saint Louis (Vannier et al., 1984) pioneered high efficiency computational methods for producing 3D reconstructions of hard and soft tissue structures from high resolution CT images, setting precedents for clinical assessments and surgical planning, as well as for rapid production of anatomical 3D models (as will be discussed further, below). Computed tomography continues to be a mainstay of clinical cross-sectional imaging, of particular value in dense tissue (e.g., bone) imaging and trauma assessment.

Ultrasonography

Historically, the development of ultrasound imaging commenced soon after the discovery of X-rays, based on physics research into the piezoelectric effect: Electrical pulsing of a crystal produced resonance and emission of an ultrasonic burst that could be transmitted through fluid and reflected by dense objects (Donald, 1974; Hendee, 1989). Early ultrasound transducers were first used for bottom-sounding and detection of obstacles by ships, and refinements for military use resulted in the development of sonar (sound navigation and ranging) during World War II (Hendee, 1989). Following the war, military pulse-echo equipment became available to biomedical researchers, and early work at the University of Minnesota attempted to measure wall thickness in normal and cancerous stomach, as well studying the detection of breast tumors. Early post-war surplus scanners required that patients and specimens be immersed in water. Following the development of non-quartz crystal ultrasound transducers and improvements in image quality, immersion tanks were eventually replaced in the 1960s with the use of compound contact scanners with mechanical transducer arms, facilitating clinical applications.

By the 1970s, original analog echo signal outputs and black-and-white oscilloscope displays were supplanted by analog then digital (computerized) scan converters that recorded and displayed gray scale images, for significant advances in image quality and clinical usefulness. Subsequent improvements in transducers, arrays, and computer image processing and the application of Doppler frequency shift data (for detection of fluid movement) raised the clinical diagnostic utility of ultrasound to unexpected levels (e.g., fetal organ blood flow measurements). Current portable 3D/4D ultrasound scanners are easily capable of generating dynamic 3D images of a fetus in utero, as well as allowing students self-discovery of heart valve functions and abdominal organs in anatomy teaching laboratories (Ivanusic et al., 2010; Griksaitis et al., 2012; Sweetman et al., 2013; Torres et al., 2016).

Magnetic Resonance Imaging

Early physics research on the magnetic properties of elemental nuclei produced seminal discoveries in the 1920s and 1930s, progressively leading to the development of nuclear magnetic resonance (NMR) technology. It was established that a variety of nuclei, including hydrogen protons, each behaved differently in a strong magnetic field, in a manner characterized by the magnetic moment of its component particles. When placed in a strong magnetic field and pulsed with radio waves, specific nuclei would emit characteristic radio frequency signals. This was the basis for the development of NMR spectroscopy, which could identify the chemical constituents of samples for chemical and biochemical analyses (Rabi et al., 1938a,b).

In the early 1970s, amidst work on applying NMR to analysis of tumor biology, efforts began to reconstruct images from resonance signals. Extremely strong and uniform magnetic fields were found to be necessary for forming useful images from nonhomogeneous body structures (Lauterbur, 1973), and in 1974, the first image of a mouse was made, highlighting a cervical fracture. By 1977, field-focusing NMR technology (FONAR) yielded the first image of a human thorax. Additional improvements in speeding sampling, scanning, and data acquisition and in generating extremely high intensity magnetic fields in the late 1970s paved the way for the first clinical trials and commercially successful clinical MR imaging scanners in the early 1980s. Use of cryogenic superconducting magnets, differentiating tissues by pulse sequence relaxation constants (T1 and T2), and multi-slice scanning helped establish MRI as a new standard for 3D soft tissue imaging.

Michael Vannier and colleagues at the Mallinckrodt Institute of Radiology in St. Louis, MO pioneered multispectral MRI image analysis for automatically differentiating and segmenting soft tissue types (Vannier et al., 1985), as well as volumetric (voxel-based) 3D reconstruction techniques (Vannier et al., 1988). The latter also produced the first clinically based dynamic 3D models that formed a new non-invasive diagnostic modality: electrocardiographic (ECG) gated MRI of the heart. More recent advances in MR image acquisition and analysis (e.g., diffusion tensor) have facilitated the rise of 'functional imaging' (Savoy, 2012), providing the potential for other new clinical and educational resources that dynamically demonstrate the molecular-level functionality of imaged tissues.

Imaging and Anatomical Sciences Education

With the evolution of health sciences curricula over the last three decades, increasing emphasis has been given to teaching anatomy integrated with clinical imaging, in order to prepare new graduates with the ability to recognize diagnostically significant morphology in radiographs, CT, MR, and ultrasound imaging (Sugand et al., 2010). In 2006 the Mayo Medical School in Rochester, MN, was one of the first in the United States to provide first-year gross anatomy students with volumetric high-resolution CT scans that were obtained from their dissection laboratory cadavers after embalming (Bartholomai et al., 2006, 2007; Wiesmann et al., 2007). Using a Web-based computer system, students could examine radiologic features and relationships in cadavers that they dissected, in addition to accessing de-identified clinical examinations of body donors (Bartholomai et al., 2006, 2007; Wiesmann et al., 2007). Some newer curricula have also proactively integrated medical imaging with anatomy components based on principles of clinical relevance (Kish et al., 2013), especially in active laboratory settings that emphasize reinforcement of three dimensional anatomical relationships (Zumwalt et al., 2010). It has also been argued that teaching 'living anatomy' with medical imaging can supplant cadaver laboratories (McLachlan, 2004; McLachlan et al., 2004).

The anatomical sciences education literature has begun to accumulate evidence evaluating clinical imaging use and efficacy in learning. Initial studies using cross-sectional anatomy images in conjunction with corresponding CT and MR sections demonstrated high cognitive load for more complex learning resources (Khalil et al., 2008), but they were unable to show positive effects on structural recognition in testing with radiological images. Lufler et al. (2010) found that students who used computer-accessible CT scans of class cadavers had significantly higher overall performance on examinations and on spatial relationship questions, compared with those who did not use the CT scan resources.

Initial studies of ultrasound (US) usage in teaching "living" thoracic anatomy demonstrated strongly positive student evaluations for effectiveness in teaching, reinforcement of lecture concepts, and stimulation of student interest (Ivanusic et al., 2010). A controlled comparison between the use of prosections and live ultrasound imaging in learning cardiac anatomy suggested that there were no significant differences in student examination performance between the separate study modalities (Griksaitis et al., 2011). Jamniczky et al. (2015) have reported that the need to learn technical aspects ("knobology") of ultrasound negatively affected student perceptions of its utility in learning anatomy for physical examination, suggesting additional efforts were needed to provide a basic technical introduction to US prior to living anatomy sessions. Finally, Jurjus et al. (2014) have provided evidence that with minimal training, anatomists can teach living anatomy using US just as well as clinicians in human anatomy courses. This study as well as others (Pawlina and Drake, 2015) encouraged anatomists to undergo US training and to utilize it in the gross anatomy curriculum.

THE VISIBLE HUMAN PROJECT AND INTERNET-BASED HUMAN STRUCTURAL IMAGING DATABASES

The Visible Human Project (VHP; Spitzer and Whitlock, 1998; Ackerman, 2002; Baatz, 2004) was another innovation related to historical cross-sectional anatomy, funded by the National Library of Medicine (NLM). This Project was originally conceived as part of the federally funded High Performance Computing and Communications (HPCC) program of the National Information Infrastructure Initiative (NII; also known popularly as "the Information Highway"), aiming to share patient data and medical images, to establish telemedicine projects providing consultation and medical care to patients in rural areas, and to facilitate development of advanced computer simulations of human anatomy for training in "virtual surgery" (Lindberg, 1995; Spitzer and Scherzinger, 2006). "Virtual anatomy" and simulation will be covered further in the next Section.

The original Visible Male data set included 1,878 digitized photographic cross-sections cut at 1-mm intervals, and the Visible Female included 5,189 sections at 0.33-mm intervals (Spitzer and Whitlock, 1998). The digital image set for Visible Human Male and Female was truly massive for the era: the digitized photographic sections plus MRI and CT data occupy about 64 gigabytes (GB), approximately the amount of data that can be contained on 16 digital video discs (DVDs). The NLM facilitated further development of these data by distributing them freely under license. Numerous research projects and commercial development programs exploited the early VHP data, with the initial result that many health science schools developed their own local instructional resources for teaching cross-sectional anatomy. The NLM also produced AnatLine, a prototype Internet database "portal" that allowed search engine-based access to Visible Human images and 3D renderings (Strupp-Adams and Henderson, 1999). Jastrow and Vollrath (2003) have provided a comprehensive review of online, CD-ROM, and print-based anatomy teaching resources produced using VHP digitized section images; other VHP-derived 3D teaching applications will be considered more specifically in the following section on simulation and modeling.

Separately, the University of Washington Digital Anatomist Project expanded its archive of digital cross-section data, derived 3D images and animations for access via the Web (Brinkley et al., 1997; Rosse et al., 1998). The Digital Anatomist Project provided early free access to digital atlases and demonstrated several accomplishments in visualization and artificial intelligence (Brinkey et al., 1997; Wong et al., 1999). Stanford University developed its own Visible Female Project, by using a 32-year-old donor body, intended to be a better source for baseline anatomical data for a reproductive-age woman than the 59 year-old NLM Visible Female donor. From these data, they produced a virtual-reality model of the pelvic region, "Lucy," intended for research and instructional use (Heinrichs et al., 2004).

Other comparable international efforts were launched following the original Visible Human Project, including the Visible Korean Human (Kim et al., 2002; Shin et al., 2015; Kwon et al., 2015), the Chinese Visible Human (Liu et al., 2013). These projects implemented technical improvements over the U.S. VHP data sets, including finer sectioning (1 mm for the Korean efforts), 'gapless sectioning' (the original

Visible Male was cut into three longitudinal parts, leaving gaps), and smaller pixel size for the digital images (Korean data supporting imaging of structures as small as 0.2 mm) (Dai et al., 2012). It has been recognized that key anatomical and clinically relevant structures might not be identifiable for modeling and simulation tools based on VHP sections (Kraima et al., 2006).

Funded as part of the National Science Foundation's Next Generation Internet initiative the Visible Embryo Project could easily be considered the offspring of the NLM-funded Visible Human Project. More than just a data set development effort, the Visible Embryo Project aimed to develop a structured and organized collaborative database resource (Doyle et al., 1996). The project was headed by investigators from George Mason University, with digitization of the Carnegie embryo collection hosted by the Human Developmental Anatomy Center at the US Armed Forces Institute of Pathology (AFIT).

The Human Brain Project was another large-scale U.S. federally funded structural database initiative directed at integrated neuroanatomical imaging and brain-mapping, and along with a number of other institutions, the University of Washington Digital Anatomist Project also participated in its various objective programs (Toga and Thompson, 2001; Brinkley and Rosse, 2002). Early products included interactive brain atlases (Brinkley and Rosse, 2002), and later work by Nowinski and colleagues (Nowinski, 2008; Nowinski et al., 1997, 2009, 2012a, 2012b; Nowinski and Chua 2013; Nowinski et al., 2015) greatly advanced the objectives of functionally integrating imaging-based stereotaxic-precision atlases into clinically useful tools for neuroradiology and neurosurgery.

THREE-DIMENSIONAL SIMULATION, MODELING, AND VIRTUAL REALITY

Virtual reality (VR) is a popular contemporary term that applies variably to the use of computers to create interactive simulated environments, or in the case of gross anatomy, to create 3D structural simulations. The modern technology had its roots in three-dimensional (3D) imaging and early interactive displays of environmental panoramas, followed by the development of the first flight simulators in the late 1960s. Initial systems used advanced computer graphics to produce 3D displays, typically with viewing systems that displayed different image perspectives to the left and right eyes to simulate stereoscopic image perception.

Photographic 3D viewing technologies had been popularly available since Victorian times, with the availability of the handheld stereopticon viewer and the popular stereoscopic postcards. During the mid-twentieth century, the public became familiar with the updated Sawyer View-Master stereopticon that used discs ("reels") containing left/right pairs of 35 mm. photographic slide transparencies, as well as rare popular cinema films that relied on viewers wearing polarized or red/blue glasses (Patterson, 2009; Gruber, 2105). The classic Bassett collection (Bassett, 1952–1963) was an outstanding, extensive set of Sawyer's View-Master Kodachrome slide reels of beautiful anatomical dissections with descriptive text/books.

The author fondly remembers special anatomy lecture sessions from the later 1970s, when medical school classes, equipped with polarized viewing glasses, could view regional anatomy from Bassett slides (Bassett, 1952–1963) displayed on the lecture hall screen by a View-Master optical projector (Stereocraft Engineering Co., Portland OR). Concerted efforts to create 3D "virtual anatomy" using computer-based stereoscopy began in the early 1990s (Trelease, 1994, 1996, 1998), and this technology has been more recently advanced with improvements in high resolution and high speed computer displays (Nguyen and Wilson, 2009).

An alternative method of producing interactive 3D images relies on two-dimensional object movement to provide an illusion of 3D structure (Trelease et al., 2000; Trelease and Rosset, 2008). Interactive, freely rotating digital image models can be produced with 3D modeling software, digital photography of physical specimens (Nieder et al., 2000), or thanks to current software incorporating methods pioneered by Vannier et al. (1984, 1985, 1988), by processing of CT and MRI clinical imaging data sets (Trelease and Rosset, 2008; Trelease and Nieder, 2013). Initial efforts were also made to support Web-based 3D anatomical models with virtual reality modeling language (VRML) (Warrick and Funnell, 1998). Early evidence indicates that individual student spatial visualization ability and problem-solving strategies affect learning with such 3D modeling learning resources (Nguyen et al., 2014).

A variety of projects have produced practical simulation and virtual anatomy tools as envisioned by the Visible Human Project leaders (Spitzer and Whitlock, 1998; Spitzer and Scherzinger, 2006), and a number of these have been tested in anatomical sciences education. Brenton et al. (2007) reported on the development and implementation of prospective, multi-institution collaboration (WebSET Consortium) to develop "Web3D" gross anatomy learning resources based on the VHP dataset, multi-source volumetric modeling, and medical imaging. Kim et al., (2007) detailed the design and development of a deformable human kidney model for a mixed reality laparoscopic surgical simulation system using VHP data and data from in vivo pig kidney mechanical properties. Nguyen and Wilson (2009) developed a detailed dynamic musculoskeletal head model as a test bed for educational applications, and separately (CT) scanned cadaveric larynx specimens were used to create 3D models for learning assessment (Hu et al., 2009). Sergovich et al. (2010) created an explorable 3D model of the female pelvis, complete with pelvic viscera and perineum.

In the neuroanatomical domain, VHP data-based 3D virtual models have been used to test the effectiveness of conventional lectures and laboratory learning (Brewer et al., 2010), to aid in learning conceptual relationships for temporal lobectomy (de Ribaupierre and Wilson, 2012), and to develop Web-based cranial nerve simulations (Yeung et al., 2011, 2012). More recently, an interactive virtual 3D model of the eye, extraocular muscles, and cranial nerve innervation was developed from VHP data, with presentation and user interface design consistent with extraneous load reduction and principles of cognitive load theory (Allen et al., 2015).

The Visible Korean Human data has been used to produce an online data set supporting browser-based self-learning and testing of sectional anatomy knowledge following lecture presentations (Shin et al., 2011). Separately, adaptive self-explorative study with 'interleaved' (combined/alternating) whole and sectional neuroanatomy using VHP and MR imagery was shown to be more efficient for learning than a basic transfer (whole then sectional) learning paradigm (Pani et al., 2013).

The U.S. VHP dataset has also spawned several commercial 3D applications, including the Visible Dissector, which has been used in studies showing comparable effectiveness to prosections and models for medical students learning cross sectional anatomy (Donnelly et al., 2009). However, careful searches of the PubMed database by this author (through August 2015) reveal relatively few studies of the educational efficacy of VHP-derived educational tools, beyond the original accounts of their development, and it is difficult to assess the scope of implementation of such anatomical simulation resources in U.S. medical school curricula.

Among existing reports, however, it is worth noting that enhanced learning of anatomical relationships has been reported for virtual 3D model use in introductory neuroanatomy (Brewer et al., 2012), for cranial nerves (Yeung et al., 2012), and for internal structure of the brainstem (Pederson et al., 2013). Positive learning effects have also been reported with the use of 3D models of the larynx (Hu et al., 2010; Tan et al., 2012). Furthermore, initial studies on the use of virtual models in undergraduate laboratories, with and instead of prosections, have demonstrated no significant learning differences between the different exclusive and combined modes, although emergent influences on social context and learning behaviors indicated the need to evaluate the effects of technology beyond the impact on knowledge gain (Hopkins et al., 2011).

Computer 3D structural modeling software has also supported the creation of physical objects, and this combined application has been put to commercial use for over two decades in "rapid prototyping" of industrial parts. For example, automotive engine parts can be modeled in computer-assisted design (CAD) software, and the resulting metal or plastic objects can be produced by a computer-controlled milling machine or "3D printer". Three dimensional modeling and "high-end" 3D printing have also come into more widespread use for surgical planning and prosthetic reconstruction over the last two decades, pointing to their relevance for medical education (Fasel et al., 2016). With the post-millennial advent of much less expensive "consumer-grade" 3D printers, anatomical education applications have begun to appear (Drake and Pawlina, 2014; Vaccarezza and Papa, 2015). Li et al. (2012) described 3D reconstruction and rapid prototype production of anatomical corrosion casts of human specimens. McMenamin et al. (2014) reported on the methods, accuracy, costs, and educational applicability of 3D printing of cadaver specimens and other structures, such as limbs, vessels, and inner ear. O'Reilly et al. (2016) have reported on the fabrication and assessment of vascularized lower limb models for teaching anatomy and for femoral vessel access training. More recent trials and applications of 3D printing for teaching anatomy are evaluating their educational efficacy (AbouHashem et al., 2015; Balaya et al., 2016; Fasel et al., 2016; Kong et al., 2016; Lim et al., 2016).

"Augmented reality" is a more recent elaboration on concepts of interactive digital 3D environments that uses primarily mobile devices to access additional information or images superimposed on real-time displays of environmental images (Zhu et al., 2014). For example, mobile phones could be used to display "pop-up" information on dissected specimens, and Google Glass could be used to show medical imaging or physiological monitoring tracked to a surgical field. These "assistive" technologies could be considered in their early infancies, still subject to major research and applications development.

Beyond macroscopic and gross anatomical 3D simulation, digital and panoramic imaging methods have also been applied to histological images, giving rise to "virtual slides," digital histology collections, and "virtual microscopy" (Downing, 1995; Trelease et al., 2000; Roth et al., 2015). A variety of different software programs have been used to scan and to "stitch together" arrays of digital images to produce very large, seamlessly scrolling and zooming "virtual slides" of individual histological specimens. Braun and Kearns (2008) reported that virtual microscopy provided increased learning efficiency and student collaboration in learning pathology, compared with prior optical microscopy methods. Mione et al. (2013) provided controlled cross-over study evidence that student learning performance with virtual microscopy is comparable to that with optical microscopy, for acquiring image-based knowledge in medical histology. Digital slide collections and "virtual microscopy" have become more widely accepted for use in microscopic anatomy laboratory instruction (Pinder et al., 2008; McBride and Prayson, 2008; Gatumu et al., 2014), and a recent American Association of Anatomists' survey showed that a majority of respondent institutions used virtual microscopy alone or in conjunction with microscopes (Drake et al., 2014).

VIDEO: FROM ANALOG TO DIGITAL AND THE YOUTUBE ERA

Transmitted analog video became a commercial commodity in the 1950s, and videocassette recorders achieved widespread consumer acceptance by the late 1970s. The availability of professional and standardized high-quality consumer video equipment supported the development of educational applications, with early proposals for anatomy examinations (Markee et al., 1965) and teaching surface anatomy (Gasser, 1972). Early commercial videos were distributed in professional ½" tape format for limited institutional use or in ¼" VHS (video home service) format for consumer video recorders.

Following the development of digital video recording and file standards in the late 1980s and early 1990s, anatomy content began to show up in additional evolving formats. First was the optical videodisc (or simply videodisc), which as previously noted, was used for storage and playback of still images before high-resolution computer graphics displays were widely available in PCs (Frisbie, 1993; Stensaas,1993; Webber et al., 1995; Downing, 1997). In some educational applications, videodiscs were replaced by CD-ROM discs which contained digital video recordings (Van Biervliet and Gest, 1995), in addition to still images and text-based data. The Anatomy Project from the University of Arkansas was an unusual, comprehensive multi-volume multimedia series that was initially available on video cassettes, videodiscs, and CD-ROMs (Gest and Van Biervliet, 1993).

However, with the development of the CD-sized digital video disc (DVD) and accompanying digital video disc read-only memory (DVD-ROM) formats, multimedia content began to appear more commonly on larger-capacity and higher image-resolution DVDs and DVD-ROM. During these periods and until the new millennium, it was common for "high-end" commercial anatomy, histology, and neuroanatomy textbooks to include additional media in enclosed CD-ROM or DVD-ROM discs. This practice was progressively eliminated in favor of providing URLs (uniform resource locater links) and codes for accessing multimedia content on publisher Web sites, although CD-ROMs may remain in use for laboratory support and other learning applications (Adamczyk et al., 2009).

By the late 1990s, the first generation of practical network-streamed digital video formats and software were released, making it possible to distribute anatomical sciences education videos via Web servers (Guttmann, 2000). These early video formats and standards were still dependent on relatively slow contemporary PC display capabilities and network/server transmissions speeds, with practical constraints on playback file size, screen resolution, video frame rates and program lengths, limiting their immediate diffusion and promoting transitional use of hybrid digital media implementations (Bacro et al., 2000; Ernst et al., 2003).

However, with continuous progressive improvements in network, data compression, and digital video format technologies, Web-distributed high resolution video became a practical tool for broader use in integrated anatomy instruction by the mid-2000s (Tabas et al., 2005; DiLullo et al., 2006; Kostas et al., 2006). With the further continuing development of high-definition (HD) digital television (HDTV), recent generations of PCs, laptops, and mobile devices became capable of playing back downloaded and networked-streamed HD video files.

Dr. Robert D. Acland from the University of Louisville developed a comprehensive, narrated video anatomy atlas of lightly embalmed dissections that was originally distributed in 1995 on VHS cassettes, and these exquisite videos have successfully migrated through DVD media to a commercially published Web archive service with interactive examination resources (Acland, 2015). Acland's videos remain in active elective use by students, and a recent study reports that Australian clinical level medical students rated them very highly among available computer-assisted learning resources (Barry et al., 2016; Choi-Ludberg et al., 2016).

One of the more common current applications of video at the institutional level has been for capturing lectures. Although current post-constructivist curricula tend to devalue lectures as inefficient "transmissive learning," many schools favor recording PowerPoint lectures, often with pointer movements and audience interactions, for later use by students (Bacro et al., 2013). This practice may also be used to facilitate later use and repurposing of prior lecture time in curricular "inversion" or class "flipping" or "blending" (Nieder and Borges, 2012; Trelease, 2015).

As an alternative, more polished educational videos can be developed de novo from storyboards and scripts, existing multimedia content, and digital video production systems. A singular, controlled, institutional study of such "off-line developed" anatomy instructional videos indicated that, although availability of these resources did not affect overall class performance on anatomy and radiology examinations, student using these resources scored significantly higher (Saxena et al., 2008).

Outside of a single institution, instructional videos have also been organized along with other multimedia learning resources in collaborative educational database archives (Sheffield, 2006). Prime examples include the Health Education Assets Library (HEAL; Candler et al., 2003) and its successor, MedEdPORTAL (Reynolds and Candler, 2008; Reilly, 2011; Shankar, 2014). In the latter instance, it has been provocatively proposed that basic undergraduate anatomical training might be conducted solely online using MedEdPORTAL content (Anderson, 2010).

In 2005, YouTube (YouTube, LLC., San Bruno, CA), the first widely adopted, free-access Web-based digital video service commenced operations, and the current public marketplace includes this and more than a dozen popular, competing services worldwide, that can be used for free or private channel educational video distribution. YouTube has since been identified as a potential distribution point and source of publicly available teaching videos (Jaffar, 2012), but preliminary studies investigating its utility in learning surface anatomy (Azer, 2012) and cardiac anatomy (Raikos and Waidyasekara, 2014) have indicated a current lack of appropriate quality content. However, a more recent Irish institutional poll of second year medical and radiation sciences students reported that about 78% of students used Web-based platforms to source YouTube as their primary source for anatomy related video (Barry et al., 2016).

"THE WEB 2.0 ERA": SOCIAL MEDIA AND LEARNING MANAGEMENT SYSTEMS

Near the turn of the second millennium, the commercial Internet 'bubble burst', and many Web-based business enterprises ("dot-coms") failed, following initial successes and promise during the 1990s. Those Web-based businesses that survived and flourished during the early 2000s demonstrated an evolved set of functional capabilities labeled "Web 2.0" by informatics publisher Tim O'Reilly (O'Reilly, 2009). As exemplified by commercial giants like Amazon (Seattle, WA), eBay (San Jose, CA), and YouTube (San Bruno, CA), successful Web 2.0 businesses employed dynamic page architectures driven by online databases that generated individualized content for users, with an underlying design that promoted their social networking (communications) focused on collaborative resource sharing (and consumption).

As opposed to original, custom-built, discipline-oriented pre-millennial Web sites supporting lectures and laboratory content, course management systems (CMSes) were developed to support multiple courses uniformly at the institutional level using Web 2.0 methods. Also known as learning management systems (LMSes), these large-scale Web server-based applications suites used database programming methods to provided password-protected student and faculty access to individual class calendars, learning materials, multimedia, online evaluation/examination, group email, and other social networking functions that facilitated collaborative work on structured coursework (Trelease, 2015). Early examples of LMSes/CMSes included Blackboard (Blackboard Inc., Washington, DC), WebCT (University of British Columbia, Canada), and Angel (Angel Learning Inc., Indianapolis, IN), which were later subsumed by the corporate expansion of Blackboard (Blackboard Inc., Washington, DC). Examples of open source systems (that could be freely obtained and customized by academic users) included Moodle (Moodle HQ, West Perth, West Australia), Drupal (Drupal Association, Antwerp, Belgium), and WordPress (WordPress Foundation, Houston, TX).

Learning management systems have become essential standards for core curriculum support in most American universities and medical schools. Evolving LMS systems have also incorporated interoperability with more recent commercial social networking tools that have become popular with Web-savvy students, including Facebook (Facebook, Inc., Menlo Park, CA), (for personalized resources and online "friend" networking), Twitter (Twitter, Inc., San Francisco, CA), (for instant, compact-size text messaging), and YouTube (YouTube, LLC., San Bruno, CA), (for user-produced digital video sharing).

Anatomists have demonstrated a variety of ways to support different aspects of learning activities with these systems. Krippendorf et al. (2007) used their LMS to log anatomy practical examination answers for automated grading. DiLullo et al. (2009) used LMS-delivered online case tutorial videos to facilitate integration of basic sciences and clinical competencies leaning in group-based discussion sessions. Wright et al. (2012) used a learning management system to integrate Web-based learning with collaborative team exercises using commercially available three-dimensional anatomical virtual dissection software and anatomical models, in a dissection-free approach to undergraduate anatomy classes. Pinelle et al. (2012) developed University of Saskatchewan Radiology Courseware (UCRS) to allow cased-based medical imaging to be easily integrated into existing course content of existing LMSes.

MOBILE DEVICES AND NEWER EMERGENT LEARNING TECHNOLOGIES

Handheld computers, more portable devices for personal computing, were first introduced commercially in the early 1990s with the Apple Newton MessagePad (Apple Corp., Cupertino, CA). At the time, with its relatively large size (4.25" × 7.25"), stylus-driven user interface, and gray scale graphics, it was widely viewed as too clumsy for widespread acceptance. Smaller personal digital assistants (PDAs) soon appeared and achieved a measure of acceptance with simple calendaring, note taking, and address book functions that let them serve as pocket-carried personal information management tools that integrated with PCs. Even with limited text and graphics display sizes, PDAs became relatively popular for business use by the end of the 1990s, and more powerful models were integrated with cellular telephones.

By the early 2000s, however, PDA sales began a pronounced decline, coincident with the rise of similarly compact personal media players (e.g., the iPod) that could also display HTML formatted text. By the mid-2000s, a new class of 'smartphones' was developed that combined PC-like computing power with higher resolution graphics, multimedia player capabilities, and PDA-like personal information management programs. Furthermore, with cellular telephone and wireless (WiFi) network connectivity and more powerful browser software, such mobile devices provided ready access to Web-based information resources and applications. Smartphones have been viewed as a paradigm-shifting 'second platform' for personal computing and scientific use (Nature, 2010), with computational power comparable to prior generation supercomputers.

Early interest was directed toward using PDAs (Menon et al., 2004; Trelease, 2004), then media players (Trelease, 2004) and smartphones (Trelease, 2008) for developing applications intended for mobile use by current generation medical students and residents (Barrett et al., 2004). All these handheld "mobile devices" were viewed as promising learning tools for millennial generation students, due to their self-adoption as "carry-everywhere" personal technology that could be used in ways consistent with the "nomadic" experience of medical education in multiple locations and clinical settings.

In 2010, a new class of mobile computing "tablets" was introduced (e.g., Apple iPad), essentially reinventing the 1990s Apple Newton with a thinner, high-resolution color touch screen display and smartphone-like capabilities. Tablets experienced very rapid diffusion within the first few years (Zickuhr and Rainie, 2014), establishing a new type of mobile applications that combined PC-class program capabilities with touch screen interactivity. Furthermore, after mobile tablets stimulated the simultaneous great rise of popularity in e-books, most major anatomical sciences textbooks have become available in e-book formats. The more widespread distribution of curricular resources in tablet-compatible formats (e.g., PDFs) has thus made it possible for students to carry with them an entire library of multimedia learning resources on a single device. The current evolution of larger smartphones ("phablets") and smaller tablets (e.g., 7" screen size) has placed a very powerfully array of networked personal educational technology in student coat pockets, usable for ubiquitous learning even in clinical locations.

Mobile computing tablets have been deployed for a variety of anatomical sciences educational applications, including primary histology and neuroanatomy learning, anatomy laboratory exercises, and 3D "virtual anatomy" structural simulations. Tablets have been used to support self-learning resources for integrated, longitudinal medical clerkships (Alegria et al., 2014). Interactive hyperlinked anatomy reviews for medical student surgical clerkships have been successfully distributed as smartphone and tablet applications, e-books, and Web-based content for PCs and tablets, starting in 2010 (Trelease, 2016). Tablets have also been used for guiding dissection laboratories (George et al., 2013; Mayfield et al., 2013). Stewart and Choudhury (2015) created and assessed the learning efficacy on the iPad of an interactive e-book for undergraduate self-guided learning about the brachial plexus. Traser et al. (2015) have reported on successful medical student use of smartphones in anatomy laboratories, for accessing online information about prosections tagged with digital QR (quick response) hyperlink codes.

DISCUSSION

E-Learning Promises

As we have seen historically, successful innovations become accepted for widespread use, and newer developments continue to arise to supplant existing technologies. Thus, as medical and educational technologies and curricula continue to evolve, there will be new opportunities for introducing innovations that can potentially enhance student learning in anatomical sciences education. Consistent with the principles of diffusion of innovations, careful proactive consideration of practical learning applications for new computing technologies, appropriate educational design and implementation planning (Gagné, 2004), well designed assessments, and publication and dissemination of project findings can facilitate the successful curricular integration of new, educationally sound, computer-based resources, and methods.

Initially, however, innovations diffuse primarily on perceived utility, without immediate objective proof that they are more effective than previously existing technologies (Rogers, 2003). This principle applies definitively to spreading educational research-based reforms in medical curricula (Colliver, 2002b), and incremental cycles of discovery and refinements of inventions are also consistent with the historical advances of basic sciences and technology (e.g., development of modern medical imaging; Hendee, 1989). Beyond the fundamentally compelling promises of technology-enhanced learning with theoretical educational principles and practices, however, there remain a variety of practical challenges, concerns, and caveats for the prospective development and implementation of computational innovations in education.

Efficacy Studies for Specific Learning Applications

In the current era, anatomical sciences education is being characterized by increasing research on the effectiveness of adult learning with different resources, methods, paradigms, and learner behavioral characteristics, and such work increasingly seeks to define objective effectiveness for innovations in computer-enhanced instruction. As with other new medical education learning practices (Colliver and Cianciolo, 2014), however, e-learning innovations in anatomical sciences education currently suffer from a scarcity of statistically reliable learning efficacy evidence. In fact, much legacy medical education research has been questioned for methodological flaws and "quasi-experimentation" with "questionable validity" (Colliver and McGaghie, 2012).

This clearly leaves more challenging work yet to be done, especially if there is to be reliable and definitive characterization of how specifically rapidly spreading new educational technology applications affect learning, positively and/or negatively, especially given seminal findings on the individual learning styles of diverse post-millennial student populations (McNulty et al., 2006; DiLullo et al., 2011; Nieder et al., 2011). Furthermore, a comprehensive review of the available literature and databases (Cook et al., 2010) has indicated that due to diversity of implementations, Web-based learning cannot be treated as a single entity in evaluations of educational efficacy. Learning resources designs and implementation methods must thus be comprehensively assessed individually in specific educational contexts in order to determine how and when they may be used most effectively.

Well-designed computer-based lectures have already been widely adopted as better than legacy photographic slide-based presentations, especially with enhancements like animations, videos, and 3D simulations, which has supported methods for the elimination of legacy anatomy lectures (Nieder et al., 2011; Nieder and Borges. 2012). Yet other evidence suggests that computer note-taking and attention-splitting in legacy lectures contribute to superficial understanding of presented information (Mueller and Oppenheimer, 2014). While constructivist learning theories, still dominating newer health sciences curricula, have devalued authoritative lectures and other 'transmissive' teaching in favor of student self-learning (Kirschner et al., 2006), a more recent trend favors 'flipping' or 'inverting' classes by requiring before-class use of online lecture resources, with class time then reserved for activities like discussions of covered content or related problem- or team-based learning exercises (Moraros et al., 2015). This process can be facilitated by using legacy lecture recordings (Nieder and Borges, 2012; Trelease, 2015), providing a transition pathway for further reducing anatomy class time in reforming integrated, multidisciplinary curricula.

For more than a decade, computers have also been put to work in medical student teaching laboratories (Lamperti and Sodicoff, 1997), for accessing Web-based learning resources and dissection instructions, hyperlinked structural information, clinical imaging, and interactive self-assessments (Rarey et al., 1995, 1997; Augustine et al., 2003; Reeves et al., 2004; Trelease, 2006b; Bartholmai et al., 2007; Adamczyk et al., 2009; Greene, 2009; Mayfield et al., 2013; Wessels et al., 2015). Despite early expressed concerns and cautions (Cahill and Leonard, 1997), computers have been used to support legacy dissection laboratories, and with demands for continuing reductions in curricular time, e-learning methods have become an integral part of streamlined, mixed resources sessions integrating prosections, plastinated specimens, skeletal materials, clinical imaging modules, structural simulations and self-learning modules (Johnson et al., 2012; Kish et al., 2013).

Large-scale human structural databases, medical imaging, and digital microscopy systems have certainly facilitated development and deployment of novel simulation resources that have no definitive proof supporting their effectiveness in completely replacing legacy laboratory methods, although their use has been advocated increasingly in the context of reduced curricular time, despite concerns about increased "cognitive load" affecting learning (Fraser, et al., 2015; Wilson, 2015). Furthermore individual student spatial visualization ability and problem-solving strategies appear to affect learning with 3D simulations (Nguyen et al., 2014).

Digital slide collections and "virtual microscopy" have become accepted for use in histology laboratory instruction (Gatumu et al., 2014) and their use is growing in U.S. medical schools (Drake et al., 2014). Currently, however, only sparse and mixed evidence supports the learning efficacy of many of these innovations in microscopic, neurological, and gross anatomy, particularly 3D models and simulations (Nicholson et al., 2006; Brewer, 2012; Khot et al., 2013; Pawlina and Drake, 2013, Yammine and Violato, 2015), even as evolving courses and curricula come to rely on them, backed by increasing demands of technologically savvy millennial students (Sugand et al., 2010; Wallace et al., 2012; Han et al., 2014).

Integrated "dissection-free" laboratories supported by computers are spreading slowly, paving the way for cadaver-free "virtual laboratories" in health sciences curricula, as well as in other undergraduate programs (Wright, 2012; Attardi and Rogers, 2015), despite continuation of legacy debates (Aziz et al., 2002; Guttmann et al., 2004; Patel and Moxham, 2006) on the value of dissection in medical school gross anatomy laboratories. While some early proponents of "cadaver-free anatomy" acknowledged a lack of evidence on its educational impact on the medical learning of anatomy (McLachlan, 2004; McLachlan et al., 2004), student examination evidence (e.g., NBME® anatomy results) has been more recently cited in support of retaining cadaver dissection laboratories (Nwachukwu et al., 2014). Surgeons and other scholars have continued to insist that, for the sake of adequate clinical grounding, use of computer resources should not replace cadaver dissections (Older, 2004; Biasutto et al., 2006; Sheikh et al., 2016). Recent evidence also suggests that models, hands-on dissection, and "virtual dissection" may have different laboratory learning consequences for individual students (Lombardi et al., 2014), with potential functional advantages still remaining for learning by dissecting.

However, despite a more recent survey showing retention of dissected cadaver laboratories by a majority of responding American medical schools (Drake et al., 2014), these practices might well be considered still at risk in institutional "authority-based" diffusion decisions (Rogers, 2003) for newer reformed curricula demanding additional reductions in basic sciences and anatomy class time. Despite the prevalence of existing clinically integrated anatomy in problem-centered adult learning curricula, continuing administrative and curricular devaluation of preclinical anatomy learning will be driven by prominent national calls for further streamlining of legacy medical school basic sciences instruction in favor of more adaptive individualized learning, early clinical immersion, and clinical competencies-focused training with standardized outcomes (Cooke et al., 2010; Irby et al., 2010; Skochelak, 2010). And remarkably, use of new technology is widely seen as vital to achieve these new curricular reforms (Skochelak, 2010). In this continuing context, future preclinical anatomical sciences education programs might come to be dominated by exclusively online lectures, and streamlined, integrated self-learning methods laboratories with minimal student use of prosected cadavers, the lattermost being reserved for later clinical specialties rotations and residency training.

As another part of the culturally evolving use of personal technologies, mobile devices, smartphones, and tablets have had widespread adoption for general use due to popular demand (Wallace et al., 2012; Hardyman et al., 2013; Zickuhr and Rainie, 2014). However, sparse early evidence suggests that their varied applications in different disciplinary and health sciences curricular contexts may be more or less successful for enhancing learning in specific contexts (Barrett et al., 2004; Alegria et al., 2014; Lumsden et al., 2015; Niehaus et al., 2015). This may depend on a number of variables, including design comprehensivity and ease of use of software, the importance of mobile learning components in a specific curricular element (class or clinical setting), and individual student learning styles and preferences.

Additional behavioral correlates of mobile technology use should be considered. In some contexts, growing concerns have been raised that casual, reflexive smartphone use can provide substantial distraction from ongoing learning activities (Papadakos, 2013). There is a growing literature on the problematic use of and dependency on smartphones and Internet connectivity (Sansone and Sansone, 2013; Roberts et al., 2014), leading to the development of assessment tools and treatment protocols for what has been termed "addictive behaviors". Furthermore, concern has been expressed about the cognitive efficiency of attention-splitting and media multitasking (Minear et al., 2013), and such in-class behaviors have been shown to be as source of distraction for nearby peers, as well as for the primary users of laptop computers (Sana et al., 2013).

Such concerns raise questions about cost-to-benefit relationships for promoting mobile learning methods in medical curricula that emphasize the support and promotion of student multitasking for necessary clinical tasks in disciplines such as surgery and emergency medicine (Bongers et al., 2015). Other evidence suggests that undergraduate students have differing capacities for efficient multitasking, and that earlier preclinical teaching methods may be inefficient during multitasking clinical work (Dubrowski et al., 2014). Together, all these factor suggests that overall effectiveness of specific m-learning methods will be a complex function of individual student multitasking capabilities and technology usage behavioral parameters, specific learning task contexts, and learning resource design features. For the foreseeable future, mobile devices might best be institutionally supported as self-selected alternative devices for preclinical online learning content (e.g., documents, Web pages, and videos; Trelease, 2015), and as resources for on-service situated learning in clerkships and residencies (Trelease, 2016).

Additional Concerns and Challenges

In a different, academic politics context, due to the aforementioned strong continuing promotion of a spectrum of adult learning theories and demands for greater use of educational technologies (Irby et al., 2010; Skochelak, 2010) in mandated reforms, administrative and curricular governance fiats may promote the elimination of legacy course activities in favor of other specific e-learning methods, with questionably sufficient evidence for learning efficacy (Colliver, 2002b; Colliver and Ciancolo, 2014). Legacy constructivist learning principles (Mayer, 1999; Colliver, 2002a; Reigeluth and Carr-Chellman, 2009), which advocate turning "the sage on the stage" to "the guide on the side", may still be used to justify the elimination of remaining lectures in favor of required, "outside class hours" online viewing of video presentations or podcasts, for "inverted" or "flipped" courses that conserve class time for interactive discussions or small group clinical problem-solving.

As an alternative, "blended" classes might simply reduce specific course hours in favor of student use of asynchronous ("do it when you like") e-learning resources, online discussion forums, simulations, and online evaluations and examinations, although evidence suggests that simplistic asynchronous practices are often inconsistent with good learning principles and knowledge retention (Barbeau et al., 2013). For hard-working anatomical sciences educators who have labored in the last decades to design and to implement creative integrated, multimodal-multidisciplinary new curricula (Churchill et al., 2009; Johnson et al., 2012) in dwindling anatomy departments, such increasing substitution of online learning for in-person course time may point to future further losses of academic privileges, "scholarly turf," personal control over teaching methodologies, and faculty appointment stature.

Another increasing concern for faculty, related to the growing use of online learning resources associated with curricular change, has been media-popularized assertions that online digital video lectures and discussion boards can economically and satisfactorily substitute for in-person university classes (Reich, 2015; Sharrock, 2015). This has been most recently exemplified by published proposals to use "massive open online courses" (MOOCs) as substitutes for in-person required coursework in medical schools, with widely shared content presented by selected "elite" instructors (Prober and Khan, 2013). Remarkably, in a medical education era dominated by principles of active adult learning, MOOCs largely promote entirely online learning at the low-yield, passive "lecture tip" of the "interactive learning pyramid," with limited network-based student-faculty interaction and with questionable results (Reich, 2015). Nevertheless, fiscally challenged American and global universities are being pressed to graduate more students in less time at lower cost by adopting "revolutionary" curricula (Christensen and Eyring, 2011) and by using more extensive online learning and MOOCs for degree credit (Prober and Khan, 2013; Rivard, 2013; Yoder, 2013) although it is unclear whether such online courses are more efficacious and less expensive than traditional courses (Cook, 2014; Sharrock, 2015).

Consistent with concerns about academic privileges, but mindful of the scholarly principles of sharing knowledge and innovations, faculty must be aware of the need for defending their academic rights and intellectual property, when producing effective e-learning media that might potentially be expropriated by free distribution or be used to supplant active faculty teaching roles. Universities and health sciences schools have varying individual policies for how much and how educational multimedia development may count for academic advancement and tenure (if it still exists for teaching anatomists at some institutions). Faculty may also be exposed to copyright violation challenges for unsecured embedded media, given free sharing of content by students via the Internet. Faculty members own the copyrights to their lectures at many U.S. universities, so e-learning materials should display copyright notices appropriate to their institutions, with appropriate acknowledgements and permissions for other published materials. Furthermore, for reducing the risks of expropriation and copyright violations, e-learning materials should be secured on a password-protected Web site or on a virtual private network.

CONCLUSION

As previously discussed, current technologies and their implementations will continue to evolve, and innovations can be applied more effectively to education as methods, practices, and educational research mature with time. In this context, it is worth considering what future innovations might reasonably be coming, based on the discussed educational technology evolution trends.

It might be seen that progressive improvements in VR and 3D printing technologies will lead to their greater, more selective adjunctive use in preclinical and clinical education settings, particularly in environments that have limited access to cadaver or plastinated specimens. However, despite the ongoing success of virtual microscopy methods for learning histology, histopathology, and neuroanatomy, high-cost whole-body virtual dissection systems and entirely student-centered exploratory learning seem unlikely "to carry the full load" of preclinical anatomy laboratory instruction, particularly with large and increasing class sizes. Furthermore given contemporary findings on the learning efficacy of various basic learning and imaging methods, along with increasing data on diversity in individual students' cognitive abilities, learning styles, and behavioral preferences, it seems most likely that mixed learning methods anatomy laboratories will prevail with minimal allotted course time, with the progression of continuing curricular reform.

In the face of prescribed progressive curricular reforms accelerating students' more rapid entry into clinical training and further compressing preclinical basic sciences time, legacy didactic introductory anatomy, and histology course time might also be supplanted by institutional or commercial online content, if not by college undergraduate course requirements for medical school admission. Certainly, the continued spread of flipped and blended courses can be expected to extend to remaining, more "conventional" preclinical and clinical curricula.

Evolving mobile technologies will persist, and they may be increasingly used for delivering asynchronous and "just-in-time" learning resources to "nomadic" students, particularly with continuing reforms in clinical curricula and widespread mobile access to clinical information systems. However, given previously reported negative learning and social aspects of smartphone use (e.g., distraction), some special educational efforts may need to be directed toward "behavioral learning" for students who grew up with habitual diversionary, "preemptive" cell phone use and social networking, especially as they might affect professional activities, such as personal interactions with patients and compliance with institutional privacy and security standards.

All things considered, from technology development to educational research and in the context of cycles of curricular reforms, the diffusion of computer-based e-learning methods has had deep influences in the evolution of the current state of anatomical sciences education. The related promises and challenges have made clear that continuing study and mastery of e-learning methods and learning efficacy research will be just as crucial to the continuing academic success of modern teaching anatomists, as mastery of integral scientific computing methods (Trelease, 2002) is to success in modern biomedical research. Furthermore, the greatest, most appropriate use of educational technology in specific curricula will remain that which is based on sound educational, scientific, and humanistic principles.

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