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Viewpoint commentary

# Histology as a paradigm for a science-based learning experience: Visits by histology education spirits of past, present, and future

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Running Title: Histology Education Past, Present, and Future

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ABSTRACT

The term 'histology' was coined a little over 200 years ago and the subject has always relied on microscopy as its defining technology. Microscopy was and still is an essential approach for the description of cellular components and their arrangements in living organisms. For more than a century and a half, histology or microanatomy has also been part of the basic science education for biomedical students. Traditionally, it has been taught in two major components, a didactic transfer of information, either in a lecture or self-learning format, and in active-learning laboratory sessions. These two modes of histology instruction conform with the dual-processing theory of learning, one being more automatic and depending mainly on rote memorization, whereas the other is analytical, requiring more advanced reasoning skills. However, these two components of histology education are not separate and independent, but rather complementary and part of a multi-step learning process that encourages a scientific analysis of visual information and involves higher-level learning skills. Conventional, as well as modern electronic instruction methods (e-learning) have been used in complementary ways to support the integrated succession of individual learning steps as outlined in this manuscript. However, as recent curricular reforms have curtailed instructional time, this traditional format of teaching histology is no longer sustainable and a reflective reassessment of the role of histology in modern biomedical education is a timely necessity.

**Keywords:** Histology education, learning theory, medical curriculum, medical education, undergraduate education, microanatomy.

*'Knowing is not enough; one must apply.*

*Willing is not enough; one must do.'*

Johann Wolfgang von Goethe (1749-1832)

(von Goethe, 2018)

INTRODUCTION

The origin and the development of histology or microanatomy as an independent scientific field was closely linked to the development of optical technologies, specifically the invention and refinement of light and later electron microscopes. For the last two centuries histology has been a foundational basic science topic that has been taught to most students of the biomedical sciences. Over the last 40 years, histology education has undergone significant changes, both in terms of didactic strategies and technologies, as well as its curricular context. This viewpoint article highlights the past evolution of histology as an educational topic and discusses its importance as an essential component of biomedical education. It will also consider the potential contributions histology can make for the education of future health care providers in the fields of human and veterinary medicine, as well as dentistry. These should include not only teaching learners the cellular architecture of metazoan organisms, but also a scientific analysis of image-based data and connecting cell and organ structures with corresponding functions.

**The history of histology**

The beginning of the fields of microscopy and histology is rooted in a Pan-European effort starting in the early 17th century. The invention of the first compound microscope, using more than one glass lens, is shrouded in mystery with several craftsmen and scientists being credited. These include two Dutchmen, spectacle maker Zacharias Janssen (1585–bef. 1632) and Cornelius Drebbel (1572-1633) and two Italians, Francisco Fontana (1580/90-1656) and Galileo Galilei (1564-1642) (Singer, 1914). The Dutch merchant and self-taught scientist Antoni Philips van Leeuwenhoek (1632-1723) used a simpler, one lens microscope design to make initial observations of microscopic organisms (van Leeuwenhoek, 1695). The optic quality of his lenses was unmatched at the time resulting in a superior image quality (van Zuylen, 1981).

Although many scientists contributed to the field of histology during its early days, four individuals stand out as its early pioneers: Robert Hooke (1635-1703) – Marcello Malpighi (1628-1694) – Marie Francois Xavier Bichat (1771-1802) and August Franz Josef Karl Mayer (1787-1865) (Figure 1). It is the Englishman Robert Hooke, who is considered to be one of the first scientists to use a simple compound microscope for the visual exploration of biological material (Gest, 2005). In his 1665 work entitled Micrographia Robert Hook introduced the term 'cell' (from the Latin *cella* for small room or chamber) into the scientific literature (Hooke, 1665). More than 150 years later and based on these first observations, Theodor Schwann and contemporaries formulated the cell theory defining the biological cell as the basic unit of all life on earth (Schwann, 1838a,b,c).

Although most of his important discoveries were made using animal specimens, starting in 1661 the Italian anatomist Marcello Malpighi is believed to be the first investigator to study the human body using a microscope (Malpighi, 1661; Saraf and Cockett, 1984; West, 2013). Among other cellular structures, he discovered capillary blood vessels as the connection between arteries and veins (Fughelli et al., 2019). This discovery provided the missing link and confirmed the 1628 description of the cardiovascular system by William Harvey in England (Harvey, 1628).

In 1800, the Frenchman Marie Francois Xavier Bichat (1771-1802) developed the concept of 'tissues' (from the old French *tissu* or woven, which itself is derived from Latin *texere* or to weave) and defined the term as it is used today (Bichat, 1800; Shoja et al., 2008). His work included a doctrine of tissue pathology and made a distinction between 21 different types of tissues. Surprisingly, his observations and descriptions were made without the use of a microscope as he mistrusted its value as a reliable scientific instrument.

In 1819, August Franz Josef Karl Mayer (1787-1865) working at the Rhenish Friedrich-Wilhelm-University of Bonn/Prussia redefined Bichat's tissue classification and in order to distinguish the new science from classical gross anatomy introduced the term 'histology' (German: *Histologie* or *Gewebekunde*) from the Greek words *ἱστός* or *histos* for web/tissue and *λογία* or *logia* for science/knowledge (Mayer, 1819).

However, up to that point, early microscopes were limited in their resolution and image quality, setting significant confines to their use as scientific and educational instruments (van Zuylen, 1981). It was the British amateur optician and physicist Joseph Jackson Lister (1786-1869), who published the first report about an achromatic lens that canceled out the spherical and chromatic aberrations which are inherent to most glass lenses (Lister, 1830). In the second half of the 19th century, further improvements to the design of the compound microscope were made, specifically by three German industrialists, opticians, and businessmen, Carl Zeiss (1816-1888), Ernst Karl Abbe (1840-1905), and Friedrich Otto Schott (1851-1935) (Volkmann, 1966; Louw et al., 2003; Wimmer, 2017). Among their main contributions were the invention of the condenser and the addition of immersion objectives, as well as the use of theoretical calculations for the industrial production of apochromatic lenses and objectives. These and other improvements enabled microscope makers in different European countries, especially the United Kingdom, Germany, France, and Italy, to build and distribute high quality instruments to the research and education communities.

These technical advances were accompanied by the development of various procedures that allow for the fixation, embedding, sectioning, and staining of biological specimens (Griffith, 1864; His, 1870; Titford, 2005, 2006). Numerous scientists contributed to the development of these procedures and supporting instrumentation, often publishing improvements of earlier versions that were developed by their peers.

As optical instruments like light microscopes are diffraction-limited, their resolution being determined by the wavelength of the light being used and their numerical aperture (Abbe diffraction limit), they are unable to depict structures smaller than 100 nm, such as most cell organelles and large biomolecules. This limitation was overcome in 1933 with the invention of the electron microscope (EM) by Ernst Ruska (1906-1988) and Max Knoll (1897-1969) (Haguenau et al., 2003). Subsequently, EM imaging significantly contributed to the discovery and investigation of subcellular organelles and compartments. EM images are now widely used in histology for educational purposes (Fawcett, 1966; Rhodin, 1975; Brueckner, 2003). With the addition of molecular and biochemical approaches, these developments resulted in histology morphing into the new field of cell biology (Scott and Logan, 2004; Bechtel, 2006).

## VISIT BY HISTOLOGY EDUCATION SPIRIT OF THE PAST

The development of histology as a research field and educational discipline that is distinct from gross anatomy is closely associated with its role as an important topic for learners of the biomedical sciences, especially medical, dental, and veterinary students (Bennett, 1956; Stewart et al., 2014; Humphrey et al., 2002; Lallier, 2014; Brown et al., 2016; Chapman et al., 2020). Starting around 1830, the use of microscopes by medical students became common at several German universities and by 1850 14 out of 19 medical schools in Germany were offering courses in microscopy (Tuchman, 1993). Friedrich Gustav Jacob Henle (1809-1885) at the University of Heidelberg and several of his colleagues at other European universities promoted the use of microscopes for the education in histology and pathology (Tuchman, 1993). By the end of the 19$^{th}$ century, microscopy had become an integral part of medical education in most industrialized countries, including many universities in North America (Kölliker, 1867; Anonymous, 1875; Orth, 1878; Böhm and von Davidoff, 1900; Cotter, 2001).

Figure 2 depicts a histology laboratory session in the year 1893 at the University of Michigan Medical School that was supervised by Gotthelf Carl Huber (1865-1934). Each student had a mono-ocular microscope for his personal use and appeared to follow instructions from an open laboratory manual (Huber, 1892). The jars and solutions on the table suggest that students had to complete some of the slide preparation and staining processes before observing the glass slides with their microscopes. The histology laboratory manuals and textbooks of that time contained detailed staining protocols (Orth, 1878; Huber, 1892; Böhm and von Davidoff, 1900; Huber, 1900), indicating that students did not rely on ready-to-use permanent glass slide collections. This made histology laboratory learning a hands-on learning activity. Only later, histology learners would receive loan collections of permanent glass slides for their laboratory sessions, liberating them from the need to process their own specimens. However, even "permanent" glass slides are prone to fading and to breakage, making their replacement a constant problem and a financial drain for educational institutions. In addition, student glass slide collections vary in quality and some rare specimens might not be available to all learners, making the sharing of slides a necessity. As a benefit, individual glass slide collections help histology learners to appreciate the variability of specimens, preparations, and biological material in general. As a necessity, all students participating in a histology course at that time learned how to operate a light microscope and some textbooks from the early days of histology instruction contained detailed chapters about microscope design and the corresponding theoretical physics (Schaffer, 1920).

During these early days of histology instruction, the technology to take photographic images of microscope observations had not been developed. Although there were earlier experimental approaches by J.B. Dancer (1812-1887) and others, microphotography only became a viable technology after 1900 (Munson, 1898; McClung, 1901; Overney and Overney, 2011). Consequently, older histology textbooks relied on woodcuts or lithographs for depicting micrographic images (Kölliker, 1867; Orth, 1878; Böhm and von Davidoff, 1900; Schaffer, 1920). Photographic reproductions in histology textbooks appeared later in the 20th century, first in black & white and later as color photographs. This initial lack of photographic images required teachers and learners in early histology laboratory sessions to produce drawing of their observations. Older histology laboratory manuals often contained empty pages for students to artistically render what they saw while examining histology slides with their microscopes (Huber, 1892, 1900; Cotter, 2001). This form of active learning results in a deeper understanding of tissue and organ structure and improves histology examination results (Cogdell et al., 2012; Kotze and Mole, 2015; Balemans et al., 2016; Cracolici et al., 2019). As this didactic approach is time consuming and requires some artistic skill by the learner, it is no longer a component of histology instruction in many countries. Nevertheless, many of the above-described strategies and approaches for teaching histology remained unchanged for more than a century and some are still being used today.

## VISIT BY HISTOLOGY EDUCATION SPIRIT OF THE PRESENT

Some technological and educational approaches for teaching histology that are described in the previous segments have seen significant changes over the last 30 years. These transformations have modified the traditional way histology has been taught, with some changes being technical in nature and others having a curricular origin.

A technology-driven change is the substitution of traditional microscopy (TM) for histology laboratory instruction by virtual microscopy (VM). First applications based on now outdated technologies of using digital images for histology and pathology teaching, like a videodisk system called 'Slice of Life', appeared in the 1980s (Stensaas and Sorenson, 1988; Kumar and Hodgins, 1990). At the end of the 20th century the use of computers had gained an increasing foothold in biomedical education and educators and students started to incorporate personal computer devices into their teaching and learning activities (Bork and Franklin, 1979; Abdulla et al., 1983). With personal computers and computer servers becoming more powerful and interconnected, it became possible to record, store, and share high resolution scanned micrographic image files (Gu and Ogilvie, 2005). For VM, high-resolution image files of histology or pathology glass slides are created using specialized microscopes with an automatic movable stage and an electronic camera. These large VM image files are assembled from smaller image tiles and stored on a computer server. Using specialized viewer software, users can access whole or subregions of a slide image with their connected electronic devices, as well as zoom in and out, similar to changing objectives with a traditional light microscope. As only the best glass slides are usually selected for digitization, VM serves as equalizer and all students learn from the same high-quality material. However, that approach also eliminates opportunities for learners to experience variabilities of slide quality and tissue/organ appearance. In 2017, 67% of US allopathic medical schools reported that they were teaching histology using only VM, 10% used only TM, 10% a combination of both TM and VM, and the remaining 13% employed only static images for histology instruction (McBride and Drake, 2018). On the other hand, VM can be an expensive system to establish and maintain and some schools are being left behind as their technological infrastructure and financial support are limited, making the introduction of VM unattainable. Consequently, the worldwide introduction of VM has been heterogenous with most industrialized countries being well ahead of developing countries in adopting this new teaching technology for histology and pathology education (Chapman et al., 2020).

Virtual microscopy has several advantages over TM, one being its ability to support team-based learning (Dickerson and Kubasko, 2007; Goldberg and Dintzis, 2007; Triola and Holloway, 2011). Histological VM images on a computer screen can be easily shared with classmates or instructors, facilitate questions, and initiate scientific discussions (Figure 3). In addition, VM is usually well-received by students as it allows them to access the material at any time and location of their choice, a flexibility that is valued by today's generation of learners (Holaday et al., 2013; Ostrin and Dushenkov, 2017). These features allow for making histology laboratory exercises a completely online event (Barbeau et al., 2013; Gadbury-Amyot et al., 2013; Yen et al., 2014; Thompson and Lowrie, 2017). Some schools, as well as many learners have followed this path to online histology laboratory education, despite attending laboratory sessions correlating with better examination results (Selvig et al., 2015).

As more and more schools completely switch to VM and drop the use of light microscopes and glass slides for histology and pathology laboratory instruction, the question has been asked whether learning the use of a traditional light microscope is still a desirable skill for medical professionals and should be taught during preclinical education (Rosai, 2007; Maybury and Farah, 2009; Pratt, 2009; Hortsch, 2015; Kuo and Leo, 2019). There is no definite answer to this question, as some medical professionals still encounter situations when, depending on their location and specialty, these skills are required. However, a majority of medical and dental students will probably never need a traditional light microscope when practicing medicine or dentistry.

Virtual microscopy is not the only contemporary e-learning strategy that is being used to teach histology. Other electronic learning resources include e-books (Young et al., 2013; Pawlina and Ross, 2018; Lowrie, 2020; Gartner and Lee, 2022), websites (UMMS, 2021), e-learning platforms (Sander and Golas, 2013; Drees et al., 2020), social media (Maske et al., 2018; Essig et al., 2020), podcasts (Beylefeld et al., 2008), online tutorials (Rosenberg et al., 2006), Massive Open Online Courses (MOOC) (Multon et al., 2018; Zhang et al., 2018), and mobile applications (Hortsch, 2016; Ostrin and Duschenkov, 2016). However, most of these e-learning approaches and resources are currently only sporadically used.

Another recent development that is changing histology instruction is the curricular integration and coordination of histology with other basic and clinical sciences (Drake et al., 2009; Yen et al., 2014). Previously, histology was often taught in stand-alone courses, independent of other parts of the curriculum (Painter, 1994; Hightower et al., 1999). As of 2017, 98% of US allopathic schools were teaching histology partially or fully integrated into their medical curriculum (McBride and Drake, 2018). The integration of histology instructions into an overall coordinated curriculum offers the opportunity to create connections and to make histology medically more relevant. This allows for better outlining structure-function relationships of tissues and cells and for connecting histological observations with biochemical reactions, physiological processes, pharmacological interactions, and pathological changes.

Most recent medical and dental curricular reforms are trying to incorporate self-directed active learning in small group settings and to make biomedical education more student-centered (Bloodgood, 2012; Khalil et al., 2013; Jurjus et al., 2018). Histology laboratory sessions are an active learning activity and making them an online learning experience caters to students' independence from scheduled didactic sessions (Holaday et al., 2013; Yen et al., 2014). Other novel didactic methods like flipped classroom strategies and gaming theory approaches have also been successfully tested for histology education but are currently not widely employed (Li and Guo, 2014; Gilliland, 2017; McLean, 2018; Felszeghy et al., 2019). Although these educational strategies have been associated with a motivational learning environment (Schumacher et al., 2013; AlFaris et al., 2014), they place responsibility onto learners for developing their own educational approaches to the material. Therefore, educators should be aware that not all students may be sufficiently prepared to thrive in such educational settings and some subjects like histology may require more active interventions by educators (Hannafin and Land, 2000; Lloyd-Jones and Hak, 2004; Kooloos et al., 2012; Hortsch and Mangrulkar, 2015).

The curricular change that had the greatest impact on histology education over the last 70 years was the decrease of instructional time for teaching histology to biomedical students (Hightower et al., 1999; Gartner, 2003; Drake et al., 2009; Drake et al., 2014; McBride and Drake, 2018). Between 1967 and 2017 a more than twofold reduction of total hours for histology instruction at US and Canadian medical schools has been reported (Figure 4). Interestingly, the two major components of histology teaching were unequally affected, with time for histology lectures receiving only modest cuts (a 35.6%

decrease) and the bulk of instructional time reduction affecting histology laboratory hours (a 75.3% decrease) (Figure 4). This reduction of time for histology education is a still ongoing process, with some North American medical school now abolishing all scheduled time for histology laboratory instruction and reducing the subject to a lecture-only format (Daniel et al., 2020; Daniel et al., 2021; Gribbin et al., 2022).

## VISIT BY HISTOLOGY EDUCATION SPIRIT OF THE FUTURE

It is a reasonable assumption that technology, as well as curricular changes will continue to have an important impact on how histology will be taught to future generations of biomedical students. In most industrialized countries, VM has been widely implemented for the teaching of histology and pathology (McBride and Drake, 2018). Mostly driven by the worldwide increasing use of telepathology, histology instruction in many developing countries is now gradually making the switch to VM and e-learning approaches (Chapman et al., 2020). With time, this movement can be expected to displace TM as the main histology teaching modus. However, TM, as well as VM both suffer from one significant limitation. They deliver two-dimensional representations of three-dimensional (3D) structures. With increasing computational power and storage capacity, 3D VM has become a reality (Kalinski et al., 2008; Eberle et al., 2014; Sieben et al., 2017; Pichat et al., 2018). Three-dimensional representations of complex histological structures hold the promise of helping students to better comprehend their complicated cellular architecture (Roth et al., 2015). On the other side, the manipulation of 3D virtual files is a time-consuming activity for learners and may not be necessary for the understanding of most histological structures. At this point, the educational value of 3D VM for the teaching of histology has not been sufficiently evaluated and very few schools have incorporated this new technology into their educational repertoire.

As outlined in the previous segment, curricular changes will continue to influence histology education. The curricular integration of histology is far advanced in many industrialized countries and will continue to proceed in educational systems where histology is still taught as a stand-alone course (Spencer et al., 2008). Integrating histology into basic and clinical science education is a sensible development, as structure-function relationships provide a foundation for other basic sciences, like physiology, biochemistry etc. Histology also bridges the gap from the macroscopic (gross anatomy) to the molecular sciences (biochemistry, physiology). By including genetic and biochemical components into histology teaching, it will become more unified with the modern version of histology, cell biology. For the first professional licensing assessment in the US, the USMLE® Step 1 examination, histology and cell biology are being tested together. In addition, histology is also foundational for histopathology and supports students' pathology competency (Nivala et al., 2013).

Furthermore, histology can serve as a more general paradigm for training preclinical students in higher-level analysis and mental processing skills. However, to stay relevant in biomedical education, histology instruction will need to relate better to the future clinical work of health science students. This is a difficult undertaking as histology is a basic science that addresses normal, healthy tissues and organs. However, it is possible to correlate normal tissue structure to pathological processes in histology examination questions (Zaidi et al., 2017). As defined by Bloom's taxonomy, such clinically inspired histology questions usually require higher level processing by the learner (Zaidi et al., 2017). Clinically relevant histology examination questions also emulate the multi-step analytic process that physicians and other health care providers must apply in the clinical setting (Croskerry, 2009; Tsalatsanis et al., 2015).

However, the major threat to histology education will remain further curricular reductions in instructional time with the most likely target being time dedicated for laboratory work (Figure 4).

## The dichotomy of histology education as described by a modified version of the dual-processing theory of learning

As described in the preceding paragraphs, histology has traditionally been taught in two major, distinct formats, one being the didactic transfer of terminology, basic knowledge, as well as histological concepts, and the other the development of recognition and visual interpretation skills. The first phase involves the memorization of cellular and acellular structures, cell and tissue types, and their functional aspects. This knowledge can be transferred to the learner using several different teaching methods and resources, first and foremost in a traditional lecture style, either delivered synchronously or as a video recording. However, students can also attain this competency by reading a textbook or by participating in a flipped classroom experience, a relatively novel educational approach that has been successfully applied to histology education (Cheng et al., 2017; Zhang et al., 2018). The second phase of histology instruction usually follows a laboratory format that involves the use microcopy, either TM or VM. Learners are confronted with unlabeled histological slide material and must analyze them by identifying structures, cells, tissues, or organs. The first didactic format of histology instruction is memory-based and non-analytic. In contrast, the second phase is deliberate and requires analytical reasoning. These two aspects of histology education can be described by the dual-processing theory of learning. This model postulates two systems of gaining and using knowledge, one in an empirical, non-analytic way and the other with an analytical and reasoning approach (Evans, 2003; De Neys, 2006; Evans and Stanovich, 2013). A similar theoretical approach has been used for the analysis of clinical reasoning (Djulbegovic et al., 2012; Tsalatsanis et al., 2015; Schuwirth, 2017). Clinical decisions are usually based on an empirical, and an analytical process. In reality, both processes are required for attaining a successful learning outcome for histology and for clinicians to analyze complex clinical situations and to reduce diagnostic errors (Norman, 2009). Therefore, in most situations, the two processes are not working in parallel, but rather interactively and synergically (Elqayam, 2009). As the skill development in a histology laboratory setting relies on the previously acquired information from the didactic phase, this is also true for histology education.

However, defining histology learning by only two steps is an oversimplification of a more intricate multi-step learning process. In a 2014 editorial, Pawlina and Drake proposed that education for the anatomical sciences is and should be a multi-modal process (Drake and Pawlina, 2014). It can be argued that histology education has been multi-phasic all along. Figure 5 shows an example of a sequential multi-step learning process for histology that is based on the author’s recommendation to histology learners at his institution. The workflow contains several sub-steps that are added to the two main parts and that have been shown to support anatomical and general biomedical education, like offering learning objectives and a review/feedback segment (Bienstock et al., 2007; Holt et al., 2015; Ruzycki et al., 2019). A range of traditional, e-learning, and novel teaching strategies and learning resources can support each step with some serving multiple steps. However, no single strategy/resource will support all steps. Such multi-step teaching approach for histology can improve student motivation and learning outcomes (Smirle et al., 2012). The exact sequence of these histology learning steps as outlined in Figure 5 might vary, depending on the availability of educational and teaching resources, the local infrastructure, the time available for histology instruction, students' individual needs, institutional and professional education goals, and more. However, the two main segments, a didactic and a laboratory-style component, remain at the center of histology instruction and removing one segment completely, like histology laboratory instruction, has a significant negative impact on the learning outcome (Gribbin et al., 2022). The outlined multi-segmental mode of histology education with its didactic and laboratory core has its origin in the past when histology became an important part of biomedical education.

## DISCUSSION

### Putting the pieces together and making an educational contribution when teaching histology to biomedical students

In an ever-changing curricular environment, histology education will have to adapt to the needs of today's, as well as tomorrow's learners. However, the essentials that every modern physician or dentist should learn during his/her education are still widely discussed and pose a difficult question without clear answers (Woolliscroft, 2019). How can histology be integrated into a wider biomedical curriculum structure? What relevance has histology knowledge for a practicing physician? Does histology laboratory instruction still provide a value for current and future health care providers? These are valid questions that need to be answered before the histology education community can offer new ways of teaching this classical subject.

A purely structural presentation of tissues and organs is no longer sufficient and must be combined with functional and pathological attributes. Modern medicine is incorporating more and more cellular and molecular aspects, such as stem cell therapy, and molecular drugs that target and modify specific types of cells, either normal or diseased. Therefore, a detailed knowledge of cellular structures and functionalities will be fundamental for the understanding of disease progression and for the development and implementation of new therapies. A first step of outlining the scope of future histology education for biomedical students is the creation of a list of core competencies which can serve as a guideline for educators and curriculum administrators. Several such syllabi for medical and dental histology instruction have recently been published (Moxham et al., 2018; Das et al., 2019; Cui and Moxham, 2021).

Traditionally, histology instruction did not extend into the molecular dimension. However, with scientific advances in several biomedical fields, more molecular details of cells, their structural components, and functional aspects are emerging. At the research level, histology has evolved into the field of cell biology and this progression should also be reflected in the educational domain. Histology and cell biology are interwoven with gross anatomy, biochemistry, physiology, genetics, and pathology. None of these disciplines is completely separated from the others and they should be taught in a coordinated curriculum organization.

The skill of analyzing micrographic images is most relevant for histopathologists and is less important for practitioners in other medical fields. However, histology laboratory experiences do support a deeper understanding of normal and abnormal tissue structure and will help physicians to read and properly interpret pathological reports. Moreover, teaching the systematic and scientific analysis of visual information, supports a broader skill that is needed for a variety of clinical activities, including, but not limited to pathology, radiology, dermatology, surgery, hematology, oncology, and others. As a multi-step learning process, histology provides a higher-level educational experience, a prized commodity in today's biomedical teaching environment. However, instructional strategies that involve higher-level analysis and thinking operations require time, time that when spent on a basic science, might delay health care students' entrance into the clinical environment.

Histology laboratory sessions with light microscopes and glass slides may no longer be sustainable and will probably disappear in favor of VM technology. Online VM instruction frees up time and caters to today's students' and school administrators' preference for flexible learning strategies and resources (Yen et al., 2014). However, laboratory exercises should remain part of the scheduled curriculum and it would be advantageous to also schedule faculty-guided sessions for those few students who learn best in a person-to-person teaching environment. As mentioned above, histology laboratory sessions also provide an excellent opportunity for evidence- and team-based learning (Van Sligtenhorst and Bick, 2011; Lallier, 2014; Ettarh, 2016).

Lastly, physicians and other health care providers are expected to make science-based diagnoses and to develop evidence-supported treatment plans. Physicians and dentists do not need to be research scientists, but they should have a full understanding of the scientific process in addition to a comprehensive knowledge of medically relevant scientific facts. Both basic science education and clinical decisions are usually based on the Socratic principle (Baker, 1990; Oyler and Romanelli, 2014). As outlined in this manuscript, clinical decision making also involves both aspects of the dual-processing model (Djulbegovic et al., 2012; Tsalatsanis et al., 2015) and biomedical science knowledge has a positive impact on diagnostic reasoning (Woods, 2007; Woods et al., 2007). To better connect both basic science and clinical education, histology educators are well advised to include clinically relevant material into their teaching, as well as in their assessment of histology learners. As defined by Bloom's Taxonomy (Zaidi et al., 2017), higher level histology examination questions usually go beyond the simple identification of histological structures and aim at applying basic science facts and recognition skills to the analysis of clinical situations. Considering that histology is a basic science and describes the structure and function of healthy cells and tissue, this requires some work and may not always be possible. However, as published by several author teams (McBride and Prayson, 2008; Shaw and Friedman, 2012), it is a worthwhile endeavor that will make histology more clinically relevant and motivates medically oriented learners.

The major threat for teaching histology to medical, dental, veterinary, and other health science students remains a lack of instructional time in today's integrated curricula. With the pressure of preparing medical, dental, and veterinary students for the clinical environment in the shortest time possible, more and more of basic science content might be deleted, offered as online-only instruction, or shifted to pre-medical/dental/veterinary school education. These actions may possibly disadvantage talented students, who are not able to afford expensive e-learning resources or did not attend colleges or undergraduate programs that are able to provide such educational opportunities.

In addition, much of professional learning is still mired in a memorization and recall mode. Elimination of histology laboratories reduces the topic to the learning of scientific facts and discourages students from engaging in a full scientific analysis. Reducing the basic sciences to a scientific fact learning effort will provide an inferior training opportunity to medical, dental, and veterinary students. Scientific knowledge is constantly evolving, and new insights are being added on an almost daily basis. Thus, biomedical education needs to be a lifelong learning activity for everybody in any health care field. A basic understanding of how scientific knowledge is obtained and how it constantly evolves provides a starting point for this process and allows physicians to adapt their diagnoses and treatment choices for their patients based on the most recent scientific evidence. In this context, histology can make a valuable contribution to the education of scientifically minded health care providers.

## CONCLUSIONS

For almost two centuries, histology has been an integral part of biomedical education with microscopy as its central technology. The traditional way of teaching histology to biomedical students has been a multi-step process involving didactic, as well as practical components. However, some past educational approaches and priorities are no longer applicable for the instruction of future health care providers. Physicians and other medical professionals are expected to deliver science-based diagnoses and evidence-supported treatment plans. This requires the ability to scientifically analyze and process available data and evidence. As many diseases and modern therapeutic strategies are cell based, a foundational histology knowledge has never been more important than today. Histology instruction can teach biomedical students a scientific analytical approach that is clinically relevant and is anchored in the Socratic Method. Appropriately integrated into basic science and clinical education, histology can provide such a science-based foundation to students of the various health science fields.

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FIGURE LEGENDS

FIGURE 1. The pantheon of early histology pioneers. From left to right are: a painting entitled ‘Portrait of a Mathematician’ attributed to Mary Beale that is believed to depict Robert Hooke (Griffing, 2020); a painting of Marcello Malpighi by Carlo Cignani; a painting of Marie-François Xavier Bichat by Pierre-Maximilien Delafontaine; and an engraving of August Franz Josef Karl Mayer by Adolf Hohnek.

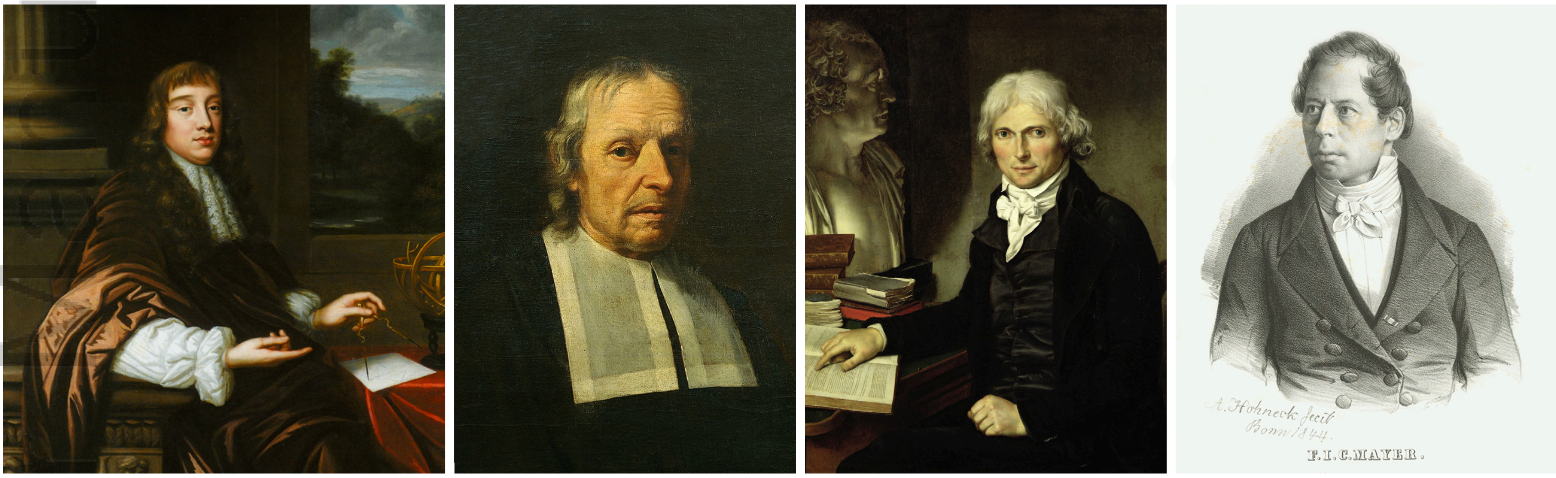
FIGURE 2. A 1893 histology laboratory session supervised by Dr. Gotthelf Carl Huber, professor of anatomy at the University of Michigan Medical School (source University of Michigan Bentley Historical Library).

FIGURE 3. A 2010 histology laboratory session at the University of Michigan Medical School. Drs. Welsh and Giger are answering a question from a medical student. Most students attending the laboratory sessions at that time were using their laptop computers to access the virtual slides on the Michigan Histology Website (UMMS, 2021).

FIGURE 4. Average time (hours) scheduled for histology education (total, lecture, and laboratory instruction) in the curricula of US and Canadian medical schools covering the timespan from 1967 to 2017. Data for the creation of this figure were extracted from five publications (Hightower et al., 1999; Gartner, 2003; Drake et al., 2009, 2014; McBride and Drake, 2018) and are based on surveys sampling the status of histology instruction

at the indicated years. The number of schools that responded to each individual survey ranged from 21 to 65.

FIGURE 5. Example of histology as a multi-step learning process. The figure shows sequential learning steps for histology that are recommended by the author to learners at his institution. EM, electron microscopy.

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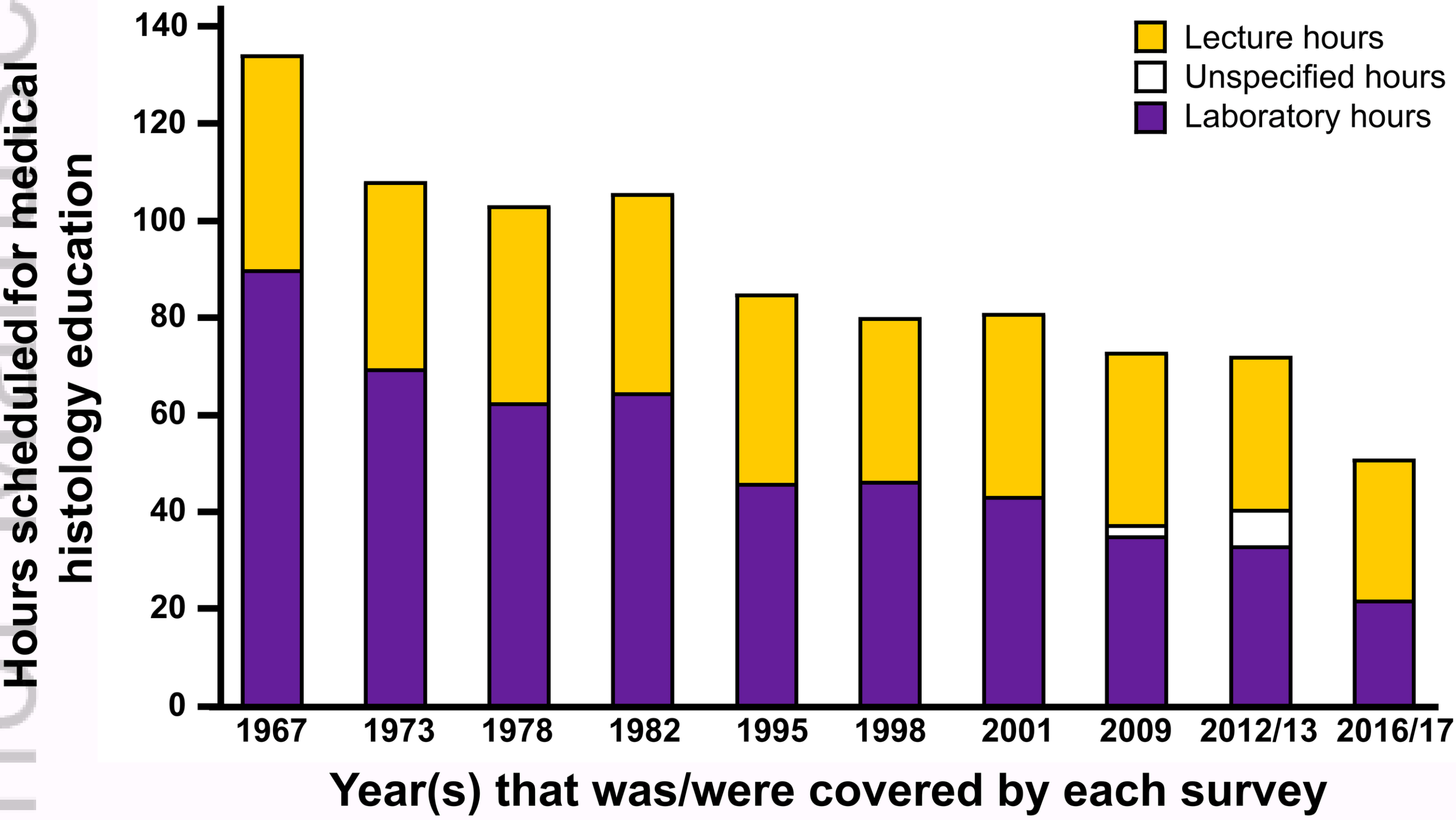


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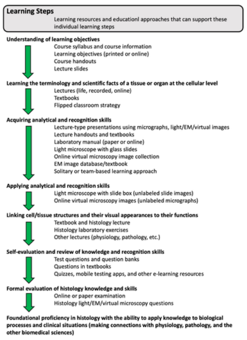


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