tvst

Perspective

Impact of Artificial Intelligence on Medical Education in Ophthalmology

Nita G. Valikodath[1], Emily Cole[1], Daniel S. W. Ting[2], J. Peter Campbell[3], Louis R. Pasquale[4], Michael F. Chiang[5], and R. V. Paul Chan[1], on behalf of the American Academy of Ophthalmology Task Force on Artificial Intelligence

[1] Department of Ophthalmology and Visual Sciences, Illinois Eye and Ear Infirmary, University of Illinois at Chicago, Chicago, IL, USA
[2] Singapore National Eye Center, Duke-NUS Medical School, Singapore
[3] Department of Ophthalmology, Casey Eye Institute, Oregon Health & Science University, Portland, OR, USA
[4] Department of Ophthalmology, Icahn School of Medicine at Mount Sinai Hospital, New York, NY, USA
[5] National Eye Institute, National Institutes of Health, Bethesda, MD, USA

Clinical care in ophthalmology is rapidly evolving as artificial intelligence (AI) algorithms are being developed. The medical community and national and federal regulatory bodies are recognizing the importance of adapting to AI. However, there is a gap in physicians' understanding of AI and its implications regarding its potential use in clinical care, and there are limited resources and established programs focused on AI and medical education in ophthalmology. Physicians are essential in the application of AI in a clinical context. An AI curriculum in ophthalmology can help provide physicians with a fund of knowledge and skills to integrate AI into their practice. In this paper, we provide general recommendations for an AI curriculum for medical students, residents, and fellows in ophthalmology.

Introduction

Although there has been a rapid evolution of artificial intelligence (AI) in medicine, there remains much to be learned regarding the implications of AI for future clinical care.[1] The concept of humans versus machines in medicine has been controversial for several decades with the introduction of new technology.[2,3] Computer algorithms have advantages in that they can process large amounts of data based on multiple parameters to determine a result or diagnosis, whereas humans use a multifactorial approach applying clinical knowledge (including the latest best medical evidence), prior experience, patient preference, and nonverbal cues to manage a patient.[4] As the practice of medicine undergoes a paradigm shift with the expansion of AI, there is a need to assimilate this new discipline into the medical education curriculum.[5,6]

Current Accreditation Council for Graduate Medical Education (ACGME) guidelines for internal medicine are being revised, as AI is anticipated to "disrupt and refine patient care practice and business models."[7] The 2019 American Medical Association (AMA) guidelines promoted the development of AI and included topics on regulation, payment, liability,

1

translational vision science & technology

and deployment.[8] Furthermore, the new AMA policy encourages the inclusion of AI in medical education by addressing AI in accrediting and licensing standards and educational modules and through enhanced training to apply data to patient care.[9] Specifically in ophthalmology, the American Academy of Ophthalmology Task Force on Artificial Intelligence was created in 2019 to identify gaps in the application of AI with regard to clinical practice and medical education.

In this paper, we explore AI in ophthalmology, perceptions of AI among the medical community, the need to adopt AI in medical education while preserving the humanization of medicine, and recommendations for an AI curriculum for medical students, residents, and fellows in ophthalmology.

AI in Ophthalmology

AI is a general term for any system that utilizes data processing and pattern recognition simulating cognitive functions, including learning and problem solving. Physicians must understand the basic concepts of AI to interpret the results of these systems appropriately as they transition toward clinical implementation. AI-assisted ophthalmic imaging modalities and analyses are quickly developing.[10] AI shows promise to favorably impact diagnostic accuracy, efficiency, access to care, health equity, and knowledge in the field of ophthalmology.

Diagnostic Accuracy and Efficiency

AI systems can perform as well as clinicians in image-based diagnoses. Specifically, studies in diabetic retinopathy (DR) have shown that AI systems can accurately detect disease with high sensitivities and specificities.[11–13] One study found that AI algorithms had higher sensitivity in detecting referable DR, severe or worse DR, proliferative DR, and diabetic macular edema compared with human experts.[14] However, algorithm performance for identifying the severity of DR can potentially be enhanced by evaluations performed by human experts.[15] In retinopathy of prematurity (ROP), significant inter-expert variability exists in classifying disease severity, especially regarding plus disease.[16,17] AI algorithms such as the i-ROP deep learning (DL) system have demonstrated high diagnostic accuracy for ROP,[18–20] outperforming experts in the field, and can be used to monitor disease progression.[21,22] Automated diagnosis in diseases such as age-related macular degeneration can improve clinical workflow by reducing the workload of physicians but have yet to be implemented or evaluated in practice.[23]

Access to Care

AI can broaden access to care for underserved populations or areas with a shortage of ophthalmologists in the United States and globally. For example, AI-assisted telemedicine platforms are being explored in screening for cataracts, ROP, and DR.[20,24,25] The US Food and Drug Administration (FDA) approved two autonomous AI systems for diabetic retinopathy: IDx-DR (Digital Diagnostics, Inc., Coralville, IA) in April 2018 and EyeArt (Eyenuk, Inc., Woodland Hills, CA) in August 2020. The FDA granted breakthrough status to the i-ROP DL system in January 2020.[26–28] In addition, an AI-integrated cataract screening program demonstrated not only high diagnostic performance but also a tenfold increase in the number of patients evaluated a year.[24] Virtual clinic models using telemedicine have been successful in retina and glaucoma by reducing costs and relieving the burden on onsite clinics.[29] Similar to the telemedicine model, AI could be incorporated into the workflow of virtual clinics to assist with diagnosis and management of ocular conditions. A virtual care clinic for type 1 diabetes has been developed that utilizes an AI algorithm to analyze a patient's insulin and glucose data and provides recommendations to physicians.[30]

Health Equity

AI has the potential to improve health equity, but there is also some concern that it can perpetuate inequity. Given that systemic biases are often engrained in data, AI models may recognize disease representations that are affected by racial, ethnic, or socioeconomic biases.[31] With thoughtful design and deployment of AI algorithms to create fair models that address inequities, protect vulnerable populations, and prevent the perpetuation of biases, AI may help improve prediction models, identify implicit social biases in documentation in the electronic health record, and create more inclusive datasets to better understand and address healthcare disparities.[32,33]

Knowledge

AI is expanding our current body of knowledge. The Google AI DL system has shown evidence of accurately predicting cardiovascular risk factors from

digital fundus images.[34] For example, information regarding age, sex, and smoking status was elucidated using features on a fundus photo. Moreover, it was recently discovered that chronic kidney disease can be accurately detected through digital fundus images and has implications for screening in the community.[35] Another study evaluating DL and retinal images showed that refractive error can be predicted primarily from foveal features.[36] Prior to these studies, we did not know that such information could be extracted from fundus photos. AI gives us the opportunity to discover new facts and to bridge gaps in our knowledge.

Perceptions of AI

With the increasing number of AI algorithms and studies being developed, it is becoming more important for physicians and medical trainees to acquire a better understanding of AI systems.[37] Trainees and certified radiologists in diagnostic radiology reported a lack of exposure to and awareness of AI tools currently used in their practice or described in the literature.[38] A group of medical students reported they had little understanding of how AI could impact clinical practice,[39] and other practicing physicians and trainees have expressed concern about potential negative career implications of AI.[38,40] At the other end of the spectrum, many in the medical field have reported believing that AI will advance their careers by playing an integral part in patient care without replacing the physician role while providing more time for academics or research.[39–41] In the United Kingdom, compared with general practitioners, biomedical informaticians were more likely to believe that AI will transform medicine.[42] These reports demonstrate the mixed perceptions of AI in the medical community. Even less is known regarding physician and trainee perspectives in ophthalmology. We conducted a survey study of members of national and regional ophthalmologic societies across the United States and found that the majority of participants believed that AI will improve ophthalmology but had concerns regarding the patient–physician relationship and diagnostic accuracy.[43]

Limitations of AI

A major concern about the adoption of AI is patient and physician acceptance due to perceived lack of transparency, as well as issues regarding safety, data usage, and perception of bias.[44,45] There is a learning curve with any new technology, but training and experience can facilitate understanding. Inaccurate results and "garbage in, garbage out" principles are important to consider when evaluating AI systems.[46] Physicians should understand the limitations of AI systems and their impact on clinical care. In addition, there are medicolegal and ethical implications for physicians who use AI.[47]

Impact of AI on the Physician's Role

The physician plays a central role in an environment that integrates AI, acting as the interpreter of this technology to improve clinical care. Historically, the x-ray and electrocardiogram revolutionized medicine by assisting in the diagnosis and treatment of patients.[48,49] Both of these technologies served as valuable supplements to the history and physical exam, but the physician was still essential for interpretation and clinical correlation of the results. This new technology is just one element that clinicians must consider in the context of the entire patient care experience.[49]

Humanization of care is a multifaceted concept that includes relationship building between the physician and patient and using a holistic approach to deliver empathy and respect in the healthcare system.[50] AI can offer new information pertinent to a patient's care while potentially saving time, allowing physicians to spend that extra time building rapport, educating, and counseling patients. Wartman et al.[51] described moving from the "information age to the age of artificial intelligence" by rebooting medical education while still maintaining compassionate care.

Physicians should be AI literate and leverage its clinical use, as medicine is shifting rapidly with the incorporation of AI tools. Physicians who embrace AI may be rewarded with better efficiency, accuracy, cost effectiveness, and enhanced patient–physician relationships in their day-to-day clinical functioning.[1]

Medical Education and AI

Historically, the Flexner Report helped to identify limitations of medical education and redefined an educational framework based on a biomedical model.[52] With reforms in education, caution must be taken not to jeopardize the quality of medical education and to maintain the standards defined in the Flexner Report.[53] Other trends in clinical practice, such as new advances in technology and the availability of more medical information, require a critical evaluation and

restructuring of our current medical education system to provide trainees with relevant information to prepare them for their future careers.[54] AI has the potential to reshape clinical practice and should be integrated into medical education. Medical trainees are interested in AI.[38] In our survey, 75% of ophthalmologists believed that AI should be incorporated into medical school and residency curricula, even those who were concerned that AI would replace physicians.[43]

Currently, AI is not discussed in the American Academy of Ophthalmology Basic and Clinical Science Course series, which serves as a fundamental resource for ophthalmology residents. The ACGME Program Requirements and Resident/Fellow Scholarly Activity do not mention AI in any subspecialty of medicine, including ophthalmology.[55,56] Furthermore, standardized tests, including the Ophthalmic Knowledge Assessment Program and the US Medical Licensing Examination, do not test on the topic of AI.[57] Incorporating AI into common educational materials and standardized tests will better ensure its integration into medical education.

AI resources for medical education are inconsistently available, and medical trainees might lack awareness of existing opportunities. Through the AMA, programs centered on partnerships between medical students and professionals have been created to help them learn how to use data to provide innovative solutions for physicians and healthcare systems.[58] For example, at the Duke Institute of Health Innovation, medical students worked on a scholarly project using an AI system for identifying predictors of early stages of sepsis and launched this model in the emergency department.[59] Medical students also attended fireside chats with physicians to discuss the use of big data in their clinical practices.[60]

Continuing medical education programs in AI include "Artificial Intelligence and the Future of Clinical Practice" and "Intro to AI and Machine Learning: Why All the Buzz."[58] These online webinars have various experts and moderators and serve as another means for physicians to understand AI and its role in clinical practice. Topics on AI have been included at major international and national ophthalmology conferences, including Association for Research in Vision and Ophthalmology meetings and American Academy of Ophthalmology annual meetings and midyear forums.[61–63] In 2019 and 2020, the University of Illinois at Chicago hosted an Artificial Intelligence in Ophthalmology Symposium featuring experts discussing AI in clinical practice, medical education, surgery, and global health.

AI educational resources can serve as a framework to better assimilate AI into medical education.

These resources should help physicians understand both established and emerging AI tools.[64] The current fragmented state of existing AI resources, trainees' interest in learning about AI, and the need to better prepare physicians for AI indicate a need for a formal AI curriculum.

Recommendations for an AI Curriculum

An AI curriculum for medical schools, residencies, and fellowships should provide information to help trainees to (1) develop the ability to appropriately utilize AI clinically, (2) understand how to interpret AI results, and 3) explain AI results to patients and other healthcare providers.[65] McCoy et al.[65] explained how AI could fit into a "reimagined medical school" concept in which a general framework pathway provides students with the knowledge that all trainees should have regarding AI and another specialized pathway is available for students who express a greater interest in the subject matter.

Structure of a Standardized Curriculum

The goals of a core AI curriculum in ophthalmology include recognizing major studies and discoveries of AI with regard to ophthalmology, identifying the limitations of AI, and learning about potential applications in clinical practice. A core curriculum could begin with lessons in basic mathematic and statistical knowledge as it relates to AI. It could then cover the fundamentals of AI, machine learning, and DL. The course could discuss a methodology for evaluating AI studies in the literature using resources such as "An Ophthalmologist's Guide to Deciphering Studies in Artificial Intelligence"[13] or "A Clinician's Guide to Artificial Intelligence: How to Critically Appraise Machine Learning Studies."[66] When this foundation has been established, seminal articles in the literature can be introduced, as well as key studies in the different subspecialties of ophthalmology. The course should highlight strengths and limitations of AI. Finally, the course should focus on how AI should be used in clinical practice, telemedicine, or virtual visits. A specialized curriculum with extracurricular activities should also be considered for trainees and clinicians desiring an in-depth understanding of AI. In fact, Faes et al.[67] showed that physicians without prior experience in coding could utilize DL algorithms to perform medical imaging classification tasks. These automated DL platforms could provide a more hands-on experience of AI. Other

Table.   Components of an AI Curriculum

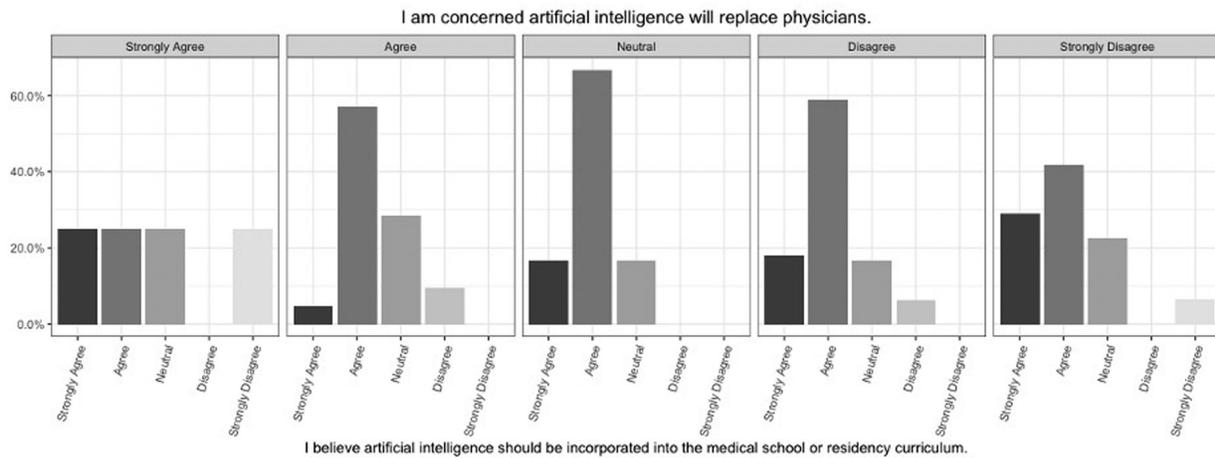| Components of a core and/or specialized curriculum |
| --- |
| Basic mathematics and statistics |
| Fundamentals of AI, machine learning, deep learning |
| How to evaluate AI literature |
| Review of seminal articles |
| Clinical applications |
| Surgical applications |
| Ethics |
| Medicolegal implications |
| Health disparities |
| Humanization of medicine |

Figure 1.   Survey results regarding belief that AI should be incorporated into training curriculum stratified by concern that AI will replace physicians.

key principles that could be integrated into the core or specialized AI curriculum are ethical implications, medicolegal aspects, health disparities, and humanization of medicine (see the Table for components of an AI curriculum). This curriculum could be implemented gradually from medical school to fellowship with a different focus at each stage.

Curriculum development for medical school, ophthalmology residency, and fellowships should ensure that each stage of training builds on the previous skill sets. The standardized AI curriculum would differ for preclinical and clinical years for medical students or by postgraduate year level for residents.[37,58] For example, in medical school, the focus could be on fundamentals of AI in medicine that are gradually incorporated through the 4 years of medical school. In ophthalmology residency, this foundation can be expanded upon during the first few years of residency

and transitioned to clinical practice and AI in the later years. See the Figure 1 for an example of a potential AI core curriculum for a 4-year ophthalmology program. In fellowship, a more specialty-specific approach can be undertaken by focusing on clinical implications and research in AI within that field.

Surgical Training

Intelligent tutoring systems have been explored in several surgical specialties.[68] A study in neurosurgery showed evidence for the potential role of AI in simulation-based training through automated feedback using proficiency performance benchmarks.[69,70] An AI system can synthesize the large volumes of data that are generated by users in a simulated scenario for training and testing, ultimately generating prediction models that produce stepwise

ARTIFICIAL INTELLIGENCE (AI) CURRICULUM				
Target Group	**Ophthalmology Residents**			
Postgraduate Year	1	2	3	4
Timeline (months)	12	24	36	48
Objectives & Competencies	1. To understand the basic components of AI 2. To identify the limitations of AI especially in healthcare and research 3. To summarize current uses of AI in ophthalmology and evaluate primary literature 4. To know how to potentially apply AI into clinical practice including telemedicine and virtual visits			
Tools for Learners	Background reading: Articles on concepts in AI, BCSC series			
	Case Studies			
	Online lecture series from experts in the field (regularly updated)			
	Interactive webinars and modules			
	Surgical simulation-based training			
	Standardized tests			
Tools for Educators	Journal clubs, educational conferences			
Tasks & Skills	Understand basic statistics and mathematics			
		Become familiar with components and functions of AI		
		Utilize web-based learning tools (articles, lectures, modules, case-based learning)		
			Assess primary literature on current AI systems in ophthalmology	
				Understand integration of AI into clinical practice

Figure 2. A proposed AI core curriculum. Adapted from Habboush Y, Hoyt R, Beidas S. Electronic health records as an educational tool: viewpoint. *JMIR Med Educ*. 2018;4(2):e10306.

feedback to users regarding their performance on the task. The incorporation of AI in surgical education could also be very useful in ophthalmology, such that many trainees could use simulated platforms such as Eyesi (Haag-Streit, Köniz, Switzerland) to practice their surgical skills. Intelligent tutoring systems could potentially improve microsurgical skills and provide a standardized method for grading surgical performance.[71]

Method of Learning

An AI curriculum should reflect the changes in methods of learning. In the past, medical education consisted of a traditional pedagogical approach with a classroom and books and using real patients to practice examination techniques and tools such as the stethoscope. Now, we see a transition from traditional learning to modernized learning with case-based learning, flipped classrooms, virtual lectures, and simulation-based training through standardized patients, online webinars, conferences, and case studies. A focus on active learning rather than passive learning should be emphasized.[65] Another aspect of teaching and learning includes personalized medical education. AI has been used to predict student performance and learning styles.[72] An Adaptive Radiology Interpretation and Education System has used a web-based platform and Bayesian networks to drive precision medical education

based on individual needs.[73] Other AI systems that use an adaptive learning environment aimed at personalized education have potential in future medical education.[74]

Future Directions

Incorporating AI into medical school, residency, and fellowship curricula will require the support of larger organizations and collaboration among programs to promote uniform adoption of a relevant curriculum. Given the complexity of such a curriculum, we recommend collaboration with the American Academy of Ophthalmology Committee for Resident Education, Association of University Professors of Ophthalmology, and American Academy of Ophthalmology. These associations can help outline a basic framework for an AI curriculum that would be integrated into medical schools, residencies, or fellowships. We also recommend a multidisciplinary approach among departments, including bioinformatics, bioengineering, computer science, and statistics, and other scientific organizations in designing AI curricula.

Expertise in AI varies among institutions. Potential solutions to this lack of uniform expertise include conferences, courses, or virtual lectures moderated by

AI experts in which trainees can participate. Existing frameworks, such as the ophthalmology advocacy curriculum or ONE Network, that incorporate online platforms developed by experts can serve as helpful online resources when building an AI curriculum.[75,76] Long-term solutions could involve faculty development programs in AI or training grants that focus on AI and medical education. Additionally, incentives can be developed by training programs to recruit experts in the field. This variability in expertise further supports the need for a standardized AI curriculum for medical education.

AI algorithms and curricula should be routinely evaluated and modified to include new information or technologies that develop over time. For example, for DR, current teachings regarding AI may be focused on image-based diagnosis, telescreening, or referral patterns, but 5 years from now this attention could shift more toward practical clinical use of the technology to help manage DR. In addition, AI could address concerns of how our diagnosis of a condition may change over time by providing a more standardized approach to grading over time. For example, in 2016, it was reported that experts diagnosed plus disease for ROP at an earlier stage of disease compared with experts in 2007.[77] A potential limitation of that study was less familiarity with wide-angle digital images in 2007 compared with 2016, which perhaps played a role in the diagnostic differences.

Big data and information technology are quickly evolving areas and pertinent to a dynamic AI curriculum. Big data is characterized by high-volume, fast processing speeds and heterogeneity.[78] In ophthalmology, clinical registries, population health databases, hospital-based biorepositories, and the electronic health record are all sources of big data that are constantly being expanded or created.[79] The AI curriculum should be modified with time as we learn more about the potential applications of AI in big data, especially its clinical use.

AI and Medical Education in Ophthalmology During and Beyond the COVID-19 Pandemic

AI is more valuable than ever in this dire period of the coronavirus disease 2019 (COVID-19) pandemic. The severe acute respiratory syndrome (SARS) epidemic in 2003 led to a fundamental shift in a Chinese medical school's method of learning to incorporate online learning techniques that persisted beyond the resolution of the epidemic.[80] Similarly, we will likely see a change in pedagogical methods due to the COVID-19 pandemic, resulting in a greater focus on virtual learning. This is an opportune time to implement AI in medical education to better understand our current pandemic and educate our future leaders. We can incorporate lessons learned from the COVID-19 pandemic, such as the advantages of incorporating virtual learning in standardized curricula. We must utilize the advantages of AI and medical education to save and protect not only our patients and healthcare workers but also all individuals in our society. AI together with medical education will be helpful in overcoming this pandemic but also preparing for life beyond COVID-19.

Conclusions

In this paper, we have described the quickly evolving impact of AI in ophthalmology and the current limited incorporation of AI in medical education, necessitating a formal AI curriculum. We have outlined basic recommendations for an AI curriculum for medical school, residencies, and fellowships. Currently, the limited AI educational resources are unevenly distributed or accessible, and there is a lack of a standardized program regarding AI in medical school, residencies, or fellowships. Advancements in AI have implications for clinical care, and physicians must understand AI to appropriately utilize this tool. The role of the ophthalmologist is fundamental to the use of this technology. As the current ACGME president and CEO, Thomas J. Nasca, MD, said regarding AI and the medical workforce, "We have to roll up our sleeves and help. We have to diversify our educational environments. We have to create a more harmonized approach to education, and we have to be better at nurturing the professional identity formation of our physicians. … We can do it together."[81] With the help of national organizations, we can reform medical education and devise a formal integrated AI curriculum in medical school, residencies, and fellowships to better equip physicians to serve their patients.

Acknowledgments

American Academy of Ophthalmology Task Force on Artificial Intelligence Members

Michael F. Chiang MD (Chair), National Eye Institute, National Institutes of Health, Bethesda, MD; Departments of Ophthalmology & Medical Informatics and Clinical Epidemiology, Casey Eye Institute, Oregon Health & Science University, Portland, OR.

Michael D. Abràmoff, MD, PhD, Departments of Ophthalmology and Visual Sciences, Electrical and Computer Engineering, and Biomedical Engineering, University of Iowa, Iowa City, IA; Digital Diagnostic, Inc., Coralville, IA.

J. Peter Campbell, MD, MPH, Department of Ophthalmology, Casey Eye Institute, Oregon Health & Science University, Portland, OR.

Pearse A. Keane, MD, FRCOphth, Institute of Ophthalmology, University College London, UK; Medical Retina Service, Moorfields Eye Hospital NHS Foundation Trust, London, UK.

Aaron Y. Lee, MD, MSCI, Department of Ophthalmology, University of Washington, Seattle, WA.

Louis R. Pasquale, MD, Eye and Vision Research Institute, Icahn School of Medicine at Mount Sinai, New York, NY.

Pietro Perona, PhD, Departments of Electrical Engineering and Computational and Neural Systems, California Institute of Technology, Pasadena, CA.

Michael X. Repka, MD, MBA, Wilmer Eye Institute, Johns Hopkins University, Baltimore, MD.

Rishi P. Singh, MD, Center for Ophthalmic Bioinformatics, Cole Eye Institute, Cleveland Clinic, Cleveland, OH.

Daniel Ting, MD, PhD, Singapore National Eye Center, Duke-NUS Medical School, Singapore.

Staff: Flora C. Lum, MD, American Academy of Ophthalmology, San Francisco, CA.

References

1. Ahuja AS. The impact of artificial intelligence in medicine on the future role of the physician. *PeerJ*. 2019;7:e7702.
2. King LS. The humanization of medicine. *JAMA*. 1975;231(7):738–739.
3. Lavine M. The early clinical X-ray in the United States: patient experiences and public perceptions. *J Hist Med Allied Sci*. 2012;67(4):587–625.
4. Lussier M-T, Richard C. Handling cues from patients. *Can Fam Physician*. 2009;55(12):1213–1214.
5. Masters K. Artificial intelligence in medical education. *Med Teach*. 2019;41(9):976–980.
6. Davenport T, Kalakota R. The potential for artificial intelligence in healthcare. *Future Healthc J*. 2019;6(2):94–98.
7. Accreditation Council for Graduate Medical Education. Revising the internal medicine program requirements using scenario planning: internal medicine 2035 executive summary. Available at: https://www.acgme.org/Portals/0/PFAssets/ProgramResources/IM2035ExSummary.pdf?ver=2018-08-16-133452-567. Accessed May 2, 2021.
8. American Medical Association. Augmented intelligence in health care. Available at: https://www.ama-assn.org/system/files/2019-08/ai-2018-board-policy-summary.pdf. Accessed April 15, 2020.
9. American Medical Association. Highlights from the 2019 AMA Annual Meeting. Available at: https://www.ama-assn.org/house-delegates/annual-meeting/highlights-2019-ama-annual-meeting. Accessed April 18, 2020.
10. Tong Y, Lu W, Yu Y, Shen Y. Application of machine learning in ophthalmic imaging modalities. *Eye Vis (Lond)*. 2020;7(1):22.
11. Abràmoff MD, Lou Y, Erginay A, et al. Improved automated detection of diabetic retinopathy on a publicly available dataset through integration of deep learning. *Invest Ophthalmol Vis Sci*. 2016;57(13):5200–5206.
12. Gulshan V, Peng L, Coram M, et al. Development and validation of a deep learning algorithm for detection of diabetic retinopathy in retinal fundus photographs. *JAMA*. 2016;316(22):2402–2410.
13. Ting DSW, Lee AY, Wong TY. An ophthalmologist's guide to deciphering studies in artificial intelligence. *Ophthalmology*. 2019;126(11):1475–1479.
14. Ruamviboonsuk P, Krause J, Chotcomwongse P, et al. Deep learning versus human graders for classifying diabetic retinopathy severity in a

nationwide screening program. *NPJ Digit Med*. 2019;2(1):25.

15. Krause J, Gulshan V, Rahimy E, et al. Grader variability and the importance of reference standards for evaluating machine learning models for diabetic retinopathy. *Ophthalmology*. 2018;125(8):1264–1272.

16. Chiang MF, Jiang L, Gelman R, Du YE, Flynn JT. Interexpert agreement of plus disease diagnosis in retinopathy of prematurity. *Arch Ophthalmol*. 2007;125(7):875–880.

17. Bolón-Canedo V, Ataer-Cansizoglu E, Erdogmus D, et al. Dealing with inter-expert variability in retinopathy of prematurity: a machine learning approach. *Comput Methods Programs Biomed*. 2015;122(1):1–15.

18. Brown JM, Campbell JP, Beers A, et al. Automated diagnosis of plus disease in retinopathy of prematurity using deep convolutional neural networks. *JAMA Ophthalmol*. 2018;136(7):803–810.

19. Coyner AS, Swan R, Campbell JP, et al. Automated fundus image quality assessment in retinopathy of prematurity using deep convolutional neural networks. *Ophthalmol Retina*. 2019;3(5):444–450.

20. Redd TK, Campbell JP, Brown JM, et al. Evaluation of a deep learning image assessment system for detecting severe retinopathy of prematurity. *Br J Ophthalmol*. 2019;103:580–584.

21. Gupta K, Campbell JP, Taylor S, et al. A quantitative severity scale for retinopathy of prematurity using deep learning to monitor disease regression after treatment. *JAMA Ophthalmol*. 2019;137(9):1029–1036.

22. Taylor S, Brown JM, Gupta K, et al. Monitoring disease progression with a quantitative severity scale for retinopathy of prematurity using deep learning. *JAMA Ophthalmol*. 2019;137(9):1022–1028.

23. Du X-L, Li W-B, Hu B-J. Application of artificial intelligence in ophthalmology. *Int J Ophthalmol*. 2018;11(9):1555–1561.

24. Ting DSJ, Ang M, Mehta JS, Ting DSW. Artificial intelligence-assisted telemedicine platform for cataract screening and management: a potential model of care for global eye health. *Br J Ophthalmol*. 2019;103(11):1537–1538.

25. Abràmoff MD, Lavin PT, Birch M, Shah N, Folk JC. Pivotal trial of an autonomous AI-based diagnostic system for detection of diabetic retinopathy in primary care offices. *NPJ Digit Med*. 2018;1:39.

26. Eyenuk. Eyenuk announces FDA clearance for EyeArt autonomous AI system for diabetic retinopathy screening. Available at: https://www. eyenuk.com/us-en/articles/news/eyenuk-announces-eyeart-fda-clearance. Accessed May 2, 2021.

27. US Food and Drug Administration. FDA permits marketing of artificial intelligence-based device to detect certain diabetes-related eye problems. Available at: https://www.fda.gov/newsevents/newsroom/pressannouncements/ucm604357.htm. Accessed September 1, 2020.

28. National Eye Institute, National Institutes of Health. Tech that detects cause of preemie blindness gets federal nod. Available at: https://www.nei.nih.gov/about/news-and-events/news/tech-detects-cause-preemie-blindness-gets-federal-nod. Accessed January 10, 2021.

29. Korot E, Wood E, Weiner A, Sim DA, Trese M. A renaissance of teleophthalmology through artificial intelligence. *Eye (Lond)*. 2019;33(6):861–863.

30. HIT Consultant. DreaMed launches AI-powered virtual clinic to help type-1 diabetics control their condition in quarantine. Available at: https://hitconsultant.net/2020/04/15/dreamed-launches-ai-powered-virtual-clinic/. Accessed December 30, 2020.

31. Rajkomar A, Hardt M, Howell MD, Corrado G, Chin MH. Ensuring fairness in machine learning to advance health equity. *Ann Intern Med*. 2018;169(12):866–872.

32. Parikh RB, Teeple S, Navathe AS. Addressing bias in artificial intelligence in health care. *JAMA*. 2019;322(24):2377–2378.

33. Chen IY, Joshi S, Ghassemi M. Treating health disparities with artificial intelligence. *Nature Medicine*. 2020;26(1):16–17.

34. Poplin R, Varadarajan AV, Blumer K, et al. Prediction of cardiovascular risk factors from retinal fundus photographs via deep learning. *Nat Biomed Eng*. 2018;2(3):158–164.

35. Sabanayagam C, Xu D, Ting DSW, et al. A deep learning algorithm to detect chronic kidney disease from retinal photographs in community-based populations. Available at: https://www.thelancet.com/journals/landig/article/PIIS2589-7500(20)30063-7/fulltext. Accessed July 5, 2020.

36. Varadarajan AV, Poplin R, Blumer K, et al. Deep learning for predicting refractive error from retinal fundus images. *Invest Ophthalmol Vis Sci*. 2018;59(7):2861–2868.

37. Kolachalama VB, Garg PS. Machine learning and medical education. *NPJ Digit Med*. 2018;1:54.

38. Collado-Mesa F, Alvarez E, Arheart K. The role of artificial intelligence in diagnostic radiology: a survey at a single radiology residency training program. *J Am Coll Radiol*. 2018;15(12):1753–1757.

translational vision science & technology

39. Pinto Dos Santos D, Giese D, Brodehl S, et al. Medical students' attitude towards artificial intelligence: a multicentre survey. *Eur Radiol*. 2019;29(4):1640–1646.

40. Sarwar S, Dent A, Faust K, et al. Physician perspectives on integration of artificial intelligence into diagnostic pathology. *NPJ Digit Med*. 2019;2:28.

41. Blease C, Bernstein MH, Gaab J, et al. Computerization and the future of primary care: a survey of general practitioners in the UK. *PLoS One*. 2018;13(12):e0207418.

42. Blease C, Kaptchuk TJ, Bernstein MH, Mandl KD, Halamka JD, DesRoches CM. Artificial intelligence and the future of primary care: exploratory qualitative study of UK general practitioners' views. *J Med Internet Res*. 2019;21(3):e12802.

43. Al-Khaled T, Valikodath N, Cole E, et al. Evaluation of physician perspectives of artificial intelligence in ophthalmology: a pilot study. *Invest Ophthalmol Vis Sci*. 2020;61(7):2023.

44. Castelvecchi D. Can we open the black box of AI? Available at: https://www.nature.com/articles/https://doi.org/10.1038/538020a. Accessed November 12, 2019.

45. Abràmoff MD, Tobey D, Char DS. Lessons learned about autonomous AI: finding a safe, efficacious, and ethical path through the development process. *Am J Ophthalmol*. 2020;214:134–142.

46. LeCun Y, Bengio Y, Hinton G. Deep learning. *Nature*. 2015;521(7553):436–444.

47. Price WN, Gerke S, Cohen IG. Potential liability for physicians using artificial intelligence. *JAMA*. 2019;322(18):1765–1766.

48. Science Museum. Brought to life. Available at: http://broughttolife.sciencemuseum.org.uk/broughttolife/themes/technologies. Accessed April 21, 2020.

49. Fye WB. A history of the origin, evolution, and impact of electrocardiography. *Am J Cardiol*. 1994;73(13):937–949.

50. Busch IM, Moretti F, Travaini G, Wu AW, Rimondini M. Humanization of care: key elements identified by patients, caregivers, and healthcare providers. A systematic review. *Patient*. 2019;12(5):461–474.

51. Wartman SA, Combs CD. Medical education must move from the information age to the age of artificial intelligence. *Acad Med*. 2018;93(8):1107–1109.

52. Flexner A. Medical education in the United States and Canada: a report to the Carnegie Foundation for the Advancement of Teaching, Bulletin Number Four, 1910. *Bull World Health Organ*. 2002;80(7):594–602.

53. Huecker M, Danzl D, Shreffler J. Flexner's words [ePub ahead of print]. *Med Sci Educ*, https://doi.org/10.1007/s40670-020-00986-1.

54. Emanuel EJ. Reforming American medical education. *Milbank Q*. 2017;95(4):692–697.

55. Accreditation Council for Graduate Medical Education. Specialty-specific references for DIOs: resident/fellow scholarly activity. Available at: https://www.acgme.org/Portals/0/PDFs/Specialty-specific%20Requirement%20Topics/DIO-Scholarly_Activity_Resident-Fellow.pdf. Accessed May 2, 2021.

56. Accreditation Council for Graduate Medical Education. The program directors' guide to the common program requirements (residency). Available at: https://www.acgme.org/Portals/0/PFAssets/ProgramResources/PDGuideResidency.pdf. Accessed May 2, 2021.

57. US Medical Licensing Examination. USMLE content outline. Available at: https://www.usmle.org/pdfs/usmlecontentoutline.pdf. Accessed May 2, 2021.

58. Paranjape K, Schinkel M, Nannan Panday R, Car J, Nanayakkara P. Introducing artificial intelligence training in medical education. *JMIR Med Educ*. 2019;5(2):e16048.

59. Elish MC. The stakes of uncertainty: developing and integrating machine learning in clinical care. *EPIC*. 2018;2018(1):364–380.

60. Henry TA. How AI is driving new medical frontier for physician training. Available at: https://www.ama-assn.org/education/accelerating-change-medical-education/how-ai-driving-new-medical-frontier-physician. Accessed April 19, 2020.

61. ARVO Learn. Artificial intelligence in ocular medicine: seeing into the future. Available at: https://www.arvo.org/globalassets/arvo/education/ai-online-event/2019-ai-online-event-agenda.pdf. Accessed April 19, 2020.

62. American Academy of Ophthalmology. The future of artificial intelligence in ophthalmology. Available at: https://www.aao.org/headline/future-of-artificial-intelligence-in-ophthalmology. Accessed April 18, 2020.

63. Technology, Artificial Intelligence and Telehealth. Available at: https://www.aao.org/eye-on-advocacy-article/technology-artificial-intelligence-telehealth. Accessed May 31, 2021.

64. Rampton V, Mittelman M, Goldhahn J. Implications of artificial intelligence for medical education. *Lancet Digit Health*. 2020;2(3):e111–e112.

65. McCoy LG, Nagaraj S, Morgado F, Harish V, Das S, Celi LA. What do medical students

actually need to know about artificial intelligence? *NPJ Digit Med*. 2020;3:86.

66. Faes L, Liu X, Wagner SK, et al. A Clinician's guide to artificial intelligence: how to critically appraise machine learning studies. *Trans Vis Sci Technol*. 2020;9(2):7.

67. Faes L, Wagner SK, Fu DJ, et al. Automated deep learning design for medical image classification by health-care professionals with no coding experience: a feasibility study. *Lancet Digit Health*. 2019;1(5):e232–e242.

68. Julian D, Smith R. Developing an intelligent tutoring system for robotic-assisted surgery instruction. *Int J Med Robot*. 2019;15(6):e2037.

69. Mirchi N, Bissonnette V, Yilmaz R, Ledwos N, Winkler-Schwartz A, Del Maestro RF. The Virtual Operative Assistant: an explainable artificial intelligence tool for simulation-based training in surgery and medicine. *PLoS One*. 2020;15(2):e0229596.

70. Winkler-Schwartz A, Bissonnette V, Mirchi N, et al. Artificial intelligence in medical education: best practices using machine learning to assess surgical expertise in virtual reality simulation. *J Surg Educ*. 2019;76(6):1681–1690.

71. Menozzi M, Ropelat S, Köfler J, Huang Y-Y. Development of ophthalmic microsurgery training in augmented reality. *Klin Monbl Augenheilkd*. 2020;237(4):388–391.

72. Bernard J, Chang T-W, Popescu E, Graf S. Learning style identifier: improving the precision of learning style identification through computational intelligence algorithms. *Expert Syst Appl*. 2017;75:94–108.

73. Duong MT, Rauschecker AM, Rudie JD, et al. Artificial intelligence for precision education in radiology. *Br J Radiol*. 2019;92(1103):20190389.

74. Vandewaetere M, Clarebout G. Advanced technologies for personalized learning, instruction, and performance. In: Spector JM, Merrill MD, Elen J, Bishop MJ, eds. *Handbook of Research on Educational Communications and Technology*. New York: Springer; 2014:425–437.

75. American Academy of Ophthalmology. Advocacy projects. Available at: https://www.aao.org/about/leadership-development/advocacy-projects. Accessed July 11, 2020.

76. American Academy of Ophthalmology. ONE Network Access. Available at: https://www.aao.org/international/programs/about-one-network. Accessed December 20, 2020.

77. Moleta C, Campbell JP, Kalpathy-Cramer J, et al. Plus disease in retinopathy of prematurity: diagnostic trends in 2016 vs. 2007. *Am J Ophthalmol*. 2017;176:70–76.

78. Baro E, Degoul S, Beuscart R, Chazard E. Toward a literature-driven definition of big data in healthcare. *Biomed Res Int*. 2015;2015:639021.

79. Clark A, Ng JQ, Morlet N, Semmens JB. Big data and ophthalmic research. *Surv Ophthalmol*. 2016;61(4):443–465.

80. Ahmed H, Allaf M, Elghazaly H. COVID-19 and medical education. *Lancet Infect Dis*. 2020;20(7):777–778.

81. Accreditation Council for Graduate Medical Education. The medical workforce of the future: an address by ACGME president and CEO Dr. Thomas J. Nasca. Available at: https://www.acgme.org/Newsroom/Blog/Details/ArticleID/8051/The-Medical-Workforce-of-the-Future-An-Address-by-ACGME-President-and-CEO-Dr-Thomas-J-Nasca. Accessed November 22, 2020.