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Evolution and Applications of Artificial Intelligence to Cataract Surgery

Daniel Josef Lindegger, MD,[1] James Wawrzynski, MD,[1,2,3] George Michael Saleh, MD[1,4]

Topic: Despite significant recent advances in artificial intelligence (AI) technology within several ophthalmic subspecialties, AI seems to be underutilized in the diagnosis and management of cataracts. In this article, we review AI technology that may soon become central to the cataract surgical pathway, from diagnosis to completion of surgery.

Clinical Relevance: This review describes recent advances in AI in the preoperative, intraoperative, and postoperative phase of cataract surgery, demonstrating its impact on the pathway and the surgical team.

Methods: A systematic search of PubMed was conducted to identify relevant publications on the topic of AI for cataract surgery. Articles of high quality and relevance to the topic were selected.

Results: Before surgery, diagnosis and grading of cataracts through AI-based image analysis has been demonstrated in several research settings. Optimal intraocular lens (IOL) power to achieve the desired postoperative refraction can be calculated with a higher degree of accuracy using AI-based modeling compared with traditional IOL formulae. During surgery, innovative AI-based video analysis tools are in development, promoting a paradigm shift for documentation, storage, and cataloging libraries of surgical videos with applications for teaching and training, complication review, and surgical research. Situation-aware computer-assisted devices can be connected to surgical microscopes for automated video capture and cloud storage upload. Artificial intelligence-based software can provide workflow analysis, tool detection, and video segmentation for skill evaluation by the surgeon and the trainee. Mixed reality features, such as real-time intraoperative warnings, may have a role in improving surgical decision-making with the key aim of reducing complications by recognizing surgical risks in advance and alerting the operator to them. For the management of patient flow through the pathway, AI-based mathematical models generating patient referral patterns are in development, as are simulations to optimize operating room use. In the postoperative phase, AI has been shown to predict the posterior capsule status with reasonable accuracy, and can therefore improve the triage pathway in the treatment of posterior capsular opacification.

Discussion: Artificial intelligence for cataract surgery will be as relevant as in other subspecialties of ophthalmology and will eventually constitute a future cornerstone for an enhanced cataract surgery pathway. *Ophthalmology Science 2022;2:100164 © 2022 by the American Academy of Ophthalmology. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).*

Artificial intelligence (AI) has permeated many facets of our lives, from facial, speech, and handwriting recognition to the underpinning of search engines and social media platforms, informing security protocols and ecommerce, and assisting transport and logistics systems. It has impacted many specialties in health care, too, with image and pattern recognition being two of the central themes. A number of the underlying principles of AI have been present for many years, but its recent rapid proliferation has accelerated as a result of exponential growth in computational power coupled with the availability of large data sets. In ophthalmology, AI has been successfully applied primarily in the fields of retina (including diabetic retinopathy and age-related macular degeneration) and glaucoma (including disc evaluation by OCT). The relative paucity of intraoperative applications is in part the result of the absence of large, categorized, and available datasets. However, that is rapidly changing.

Integration of technology in surgical theaters has been instrumental in the genesis of surgical data science and has the potential to substantially improve team performance and patient outcomes. The concept of amalgamation and consolidation of different tech streams into 1 operating theater has been termed the *smart operating theater*. It functions as a hub, with different building blocks interacting with each other to assist the surgeon and their team in a real-time, data-driven decision-making system. Of these components, advances in electronic patient records, surgical data, intraoperative audio-visual recording, telemedicine, virtual and augmented reality, surgical robotics, and remote communication methods linking operating theaters facilitate smart functionality. Coupled with the incorporation of other data-driven disciplines in computational science, engineering, statistics, and mathematics, the availability of information that can be used to develop the smart operating theater is growing. Artificial intelligence will be one of the

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key pillars in the functioning of the smart operating theater of the future.

In this review article, the role of AI in the cataract surgical pathway is discussed with an emphasis on its role in the preoperative, intraoperative, and postoperative phases of surgery. In the near future, AI is likely to become central to safe, effective, and efficient surgery because it will influence many aspects of the surgical workflow. The requirement for informed consent was waived because of the retrospective nature of the study. All research adhered to the tenets of the Declaration of Helsinki.

Preoperative Phase

Epidemiologic or population-based patient data from digital patient records available from the entire cataract pathway will provide the necessary data source to support the preassessment team, the surgeon, and postoperative care pathways.

Cataract Detection and Grading

In the preoperative setting, cataract detection and grading can be achieved through AI-based image analysis. Several machine or deep learning algorithms have been developed to recognize cataracts based on slit-lamp images, either from the anterior segment or through distortions of the fundus image, which allow for nuclear cataract severity grading based on standardized scales.[1] Additionally, mathematical models are capable of recognizing lens dislocation[2] and coexisting anterior segment pathologic features such as corneal haze or keratoconus[3,4] with high accuracy, thus allowing improved risk stratification and surgical planning. In the pediatric population, AI has proven effective for predicting postoperative refraction and myopic shift in children undergoing cataract surgery across a range of ages.[5]

IOL Power Calculation

Most current calculations of intraocular lens (IOL) power are based on linear formulae using biometric data. Artificial intelligence modeling allows computation of 3-dimensional surfaces based on the combination of several existing formulae, thus generating a super formula.[6] The Kane formula is another example of an AI-based approach, which bases its calculation on many different biometric parameters, such as axial length, keratometry, anterior chamber depth, and patient gender, along with optional variables including lens and central corneal thickness, to help predict the refractive outcome.[7] Such formulae are likely to be more accurate than traditional methods because they are able to incorporate complex nonlinear relationships between the ocular parameters.[8] Artificial intelligence-based lens power calculations may ultimately allow automation of the lens selection process, and therefore may aid in the reduction of human error in this process. Within a smart theater environment, AI-based lens detection could also be integrated into the technological space, allowing for an enhanced World Health Organization checklist that cross-references the electronic records. Global health research has demonstrated that machine learning can be used to optimize the IOL inventory of a cataract service in a low-resource context, which reduces postoperative refractive error by ensuring that the correct lens is present for each patient undergoing surgery.[9]

Intraoperative Phase

AI for Cataract in Theaters

Although AI has been widely adopted in the medical technology industry for diagnosis, it has not yet become standard in operating theaters. This is on the verge of changing with the advent of AI-based medical devices for image and video analysis. Significant progress has been made in computer-aided vision algorithms, allowing the automated recognition of different phases of cataract surgery in surgical videos and instrument detection and tracking.[10–12] The main function of intraoperative-based AI devices is to provide context-aware assistance, enabling surgical monitoring, duration prediction, surgical phase detection, and intraoperative risk stratification aiming to improve safety, efficiency, team communication, and overall quality of care.[13]

Intraoperative AI Devices

A commercially available AI system for ophthalmic surgery, Touch Surgery Enterprise (Medtronic plc), recently became available. Touch Surgery Enterprise is a video management and analytics solution for surgeons. It enables seamless recording and uploading of videos. For select procedures, including cataracts, AI-powered analytics are available to segment each case into phases and to provide insights on surgical workflow.[10,14]

Recently, AI enabled the introduction into theaters of voice-driven interactive systems that provide data about the operation or medical information about the patient. In addition, these systems allow the control of surgical devices and tracking of resources and materials. Such speech recognition and interaction systems blend into the concept of a smart operating theater and will become more important in ophthalmic surgery as part of the digitalization of the operating room.[15]

Surgical Teaching and Training

Technologic advances recently allowed the development of several innovations in surgical training. The recent widespread adoption of simulation, for example, has been shown to accelerate skills transfer and improve patient safety.[16–20] These systems work through an automated, objective, and numerical data capture process that generate metrics that are used to stratify performance and offer feedback to the user to help develop their skills further.[18]

Video-based assessment alone through peer-to-peer analysis has been proposed as a suitable way to improve a trainee's learning from surgery. Notably, higher peer assessment ratings based on video analysis of surgery have been associated with fewer postoperative adverse events.[21,22] In addition, a randomized study evaluating the role of video-based coaching in learning laparoscopic skills concluded that video-based coaching improved surgical performance on both virtual reality and animal models, thus maximizing improvements in surgical performance from every clinical exposure.[14] From the trainee's point of view, video-based assessment is valuable to aide exposure to a variety of senior surgeon's opinions, which may differ from the trainee's self-assessment.[23]

Machine learning (a subset of AI) was previously applied to cataract surgery and was shown to reliably discriminate junior from senior surgeons based on a variety of numerical parameters including time, instrument path length, number of movements, and higher-order parameters across both the entire procedure and individual surgical steps.[12] Recently, a more advanced AI system was also applied successfully to phacoemulsification surgery, showing that automated recognition of instrumentation and operative phases can be achieved from raw video data alone.[10,11] As the power and accessibility of this type of AI in theaters proliferates, for surgeons of all grades, the ability to form normative pools, correlation with clinical outcomes, and evaluation of broader patterns in the data will all become possible. Much like the National Ophthalmic Database allowed for evidence-based guidance of practice, so will AI afford us the tools to do the same for performance and operative flow. However, the trend will likely evolve to be applied to a much wider pedagogy, involving the entire team, just as we have seen in immersive simulation in team training.[24] The deployment of an AI system in the operating room that can recognize phases of cataract surgery, instruments, and the other metrics will benefit all members of the surgical team. For example, by displaying the information on a screen, theater nurses can improve their situational awareness through information about which instruments are currently in use, which will be requested next, and how long each phase of surgery takes on average (tailored to each surgeon's idiosyncrasies). Under the auspices of the smart operating theater, this information can be linked to patient flow in theaters, clinical outcomes through electronic patient records (EPRs), safety enhancement (for example, lens selection), or an enhanced World Health Organization checklist, along with many others.

Three-dimensional heads-up viewing platforms, which offer real-time digital video capture of surgery with subsequent video screen projection, offer further team training opportunities. Currently available devices include the Ngenuity 3-D Visualization System (Alcon, Inc) and Trenion 3-D HD (Carl Zeiss Meditec).[25] Three-dimensional video recordings, where 2 disparate cameras capture slightly different views, are becoming available now.[26] When merged, they can partially replicate the stereoscopic view as seen by the surgeon. As these become more widely available, the AI platforms will be able to undertake more detailed depth cue analysis, which will further enhance their applicability.

Integration of Multimodal Data

Artificial intelligence has been used for image analysis of OCT data in the diagnosis of both anterior and posterior segment pathologic features.[27] Intraoperative OCT devices use a broadband laser mounted to the surgical microscope to capture structural high-resolution images of the anterior or posterior segment of the eye. These provide the surgeon with additional information regarding the anatomic and pathology features and other relevant clinical details to support the surgical process. Intraoperative OCT devices have already been introduced in ophthalmology, mainly for vitreoretinal procedures to display epiretinal membranes and subretinal injections, but will likely have a role for cataract surgery with anterior chamber depth,[27] angle,[28] and other analysis, which will lend itself well to AI applications.

The Smart Operating Theaters

As the growing breadth of technology becomes incorporated into the operating room, an ever-greater volume of data in turn is generated. The intelligent or smart operating room draws together this information, incorporates high connectivity, encompasses ergonomic design, integrates a breadth of equipment, and allows for a much higher-level functionality. Ophthalmology is one specialty in which this model will be particularly useful. A perpetual challenge with data generation is its effective use, and this is where AI will prove highly valuable. Three different initiatives exist that promote smart and integrated operating theaters: the smart cyber operating theater, the medical device plug-and-play interoperability program, and the secure and dynamic networking in operating room and hospital project.[29]

AI and Robotics

In ophthalmology, feasibility and proof-of-concept studies for robot-assisted cataract surgery,[30,31] penetrating keratoplasty,[32] corneal laceration,[33] pterygium surgery,[34] and amniotic membrane transplantation[35] have been demonstrated to date. A commonly used application for semiautomated cataract surgery is the femtolaser, which performs certain steps of cataract surgery such as precise corneal incisions, well-sized capsulorrhexis, and lens fragmentation. However, an experienced operator with a thorough understanding of ocular anatomic features is still required for proper set up and use of the laser.[36]

The Preceyes Surgical robotic system (Preceyes BV) has been used in vitreoretinal surgery to allow for the subretinal application of gene therapy.[37,38] Deep learning algorithms may further enhance robotic surgery in this field in the future by needle detection using microscope-integrated OCT, as has been demonstrated ex vivo in pig eyes.[39] In cataract surgery, intraoperative OCT has been used to obtain intraoperative lens capsule measurements instead of preoperative anterior chamber depth (which is the standard on biometry machines) to better predict the postoperative IOL position, which is a well-known source of error and inaccuracy of IOL power calculation.[40] In the future, intraoperative biometry could be enhanced with AI-based predictions that have the potential to improve postoperative refractive outcomes. The potential of AI to autonomously operate robotic surgical systems has been demonstrated with the autonomous soft-tissue surgical robot.[41,42] Although the robotic system operated in a controlled laboratory setting, similar approaches may be used in the future.

Recently, assistive robotic devices were developed for use in the operating room to assist the surgeon by picking up and transferring items. An eye-tracking–based robotic scrub nurse was recently presented for laparoscopic surgery.[36]

Postoperative Phase

Patient Pathways

Ever larger volumes of data are now routinely collected throughout the entire patient pathway and include analyzable information on patient demographics, risks, complications, refractive and visual outcomes, patient-reported outcomes, and many more. At present, this is coarsely correlated with intraoperative events, but with the advent of AI, a more granular look at the intraoperative process and how this specifically correlates with certain postoperative outcomes will emerge, especially as larger datasets and more sophisticated algorithms materialize. This, in turn, will spur the advent of much more tailored health care for the individual, mirroring the genomic revolution.

A deeper understanding of the trends and influences along the entire pathway will allow not only more personalized care, but also more accurate risk stratification on a patient-by-patient basis. This, in turn, can allow the pathway to be better refined and adapted where the need arises, enabling the most effective deployment of scarce resources. An example is posterior capsular opacification, which remains a very common postoperative problem after cataract surgery. Artificial intelligence applications have been shown to successfully detect posterior capsular opacification, and therefore could help to triage patients for neodymium:yttrium–aluminum–garnet capsulotomy.[43]

On the macro scale, it is clear that AI deployment could refine many aspects of postoperative care. As better data integration between primary and secondary health care settings occurs, presently disparate sources of information will be more seamlessly integrated, which will enable postoperative data collected in the community to be evaluated by operating centers with the assistance of automated analysis by AI systems. Artificial intelligence has also been shown to help improve efficiency of scheduling patients' hospital visits and has been reported to "solve the dynamic patient admission scheduling problem."[44] Given the sheer volume of cataract surgery globally, even small-percentage gains will have a significant impact on a regional, national, or international scale.

A concept to predict operating time based on factors in the surgical environment, such as experience of surgeons, anesthetist, and support staff and the type of anesthesia, has already been demonstrated for cataract surgery, and it has the potential to increase efficiency of theater use by optimizing scheduling of procedures.[45]

The coronavirus disease 2019 pandemic has presented health care systems around the world with an unprecedented set of challenges. However, it has also forced new ways of thinking, accelerating the implementation of existing technologies that were previously underused. Remote consultations were routinely conducted during the lockdowns in the United Kingdom, and many patients and clinicians found this format convenient and preferable to face-to-face consultations for certain types of encounters. A key limitation in the cataract surgical pathway is the absence of reliable and high-quality data. The infrastructure for joined up care has already begun to be laid down, which will provide high-quality big data. A rapid deployment of AI will then be necessary to analyze these data. Such systems could enable face-to-face hospital interactions to be more precisely targeted to those who require them.

Conclusions

We are in the midst of a global health care technology revolution, which has led to many changes in the health care field as a consequence of the digital transition. In the United Kingdom, the National Health Service plan[46] includes moving to a digital-first model by 2030, whereby patients will be able to access health care via technology. This, in turn, is planned to improve vastly access, effectiveness, and efficiency. One of the central pillars of the technological revolution in health care is the use of AI because of its numerous potential benefits, as aptly described by Eric Topol.[47,48] Drives such as National Health Service user experience (NHSx)[49] and National Health Service Digital[50] will allow for safe, secure, and rapid data exchange, which are all central to successful AI use in health care. Artificial intelligence is also rapidly scalable, with an ever-expanding accessible volume of data and improved algorithms for analysis. The coronavirus disease 2019 pandemic has rapidly accelerated the need for, and the drive toward, these technological solutions as social distancing and surgical backlogs have torn down many of the traditional models of delivery, forcing newer and more innovative ways of practice.

Cataract surgery will be central to this drive because it is the most commonly performed operation both in the United Kingdom[51] and globally,[52,53] and currently has long backlogs of > 300 000 cases over and above prepandemic levels in the United Kingdom alone.[54–57]

Artificial intelligence has the potential to positively influence the entire cataract pathway, from diagnosis and risk stratification to intraoperative analytics, training and guidance and to more readily accessible after-care, while also enhancing safety and patient-centered care. The growth of technologies underpinning AI, digitization of the required data, and the enormous unmet health care need leave AI in cataract care as a tool we will all, most probably, be working with in the near future.

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[1] Moorfields Eye Hospital, London, United Kingdom.

[2] UCL Great Ormond Street Institute of Child Health, University College London, and NIHR, London, United Kingdom.

[3] Great Ormond Street Hospital Biomedical Research Centre, London, United Kingdom.

[4] NIHR Biomedical Research Centres (BRCs), London, United Kingdom.

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Author Contributions:

Conception and design: Lindegger, Wawrzynski, Saleh

Analysis and interpretation: Lindegger, Wawrzynski

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Overall responsibility: Lindegger, Wawrzynski, Saleh

Abbreviations and Acronyms:
AI = artificial intelligence; **EPR** = electronic patient record; **IOL** = intraocular lens; **NHS** = National Health Service.

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Correspondence:
Daniel Josef Lindegger, MD, Moorfields Eye Hospital, London, United Kingdom. E-mail: lindeggerdaniel@gmail.com.

References

1. Li H, Lim JH, Liu J, et al. An automatic diagnosis system of nuclear cataract using slit-lamp images. *Annu Int Conf IEEE Eng Med Biol Soc*. 2009;2009:3693−3696.
2. Xu Y, Gao X, Lin S, et al. Automatic grading of nuclear cataracts from slit-lamp lens images using group sparsity regression. *Med Image Comput Assist Interv*. 2013;16(Pt 2): 468−475.
3. Zou HH, Xu JH, Zhang L, et al. [Assistant diagnose for subclinical keratoconus by artificial intelligence]. *Zhonghua Yan Ke Za Zhi*. 2019;55(12):911−915.
4. Siddiqui AA, Ladas JG, Lee JK. Artificial intelligence in cornea, refractive, and cataract surgery. *Curr Opin Ophthalmol*. 2020;31(4):253−260.
5. Zhang X, Shi Y-y. [Prediction of myopic shift in paediatric pseudophakia using a neural network: a preliminary study]. *Zhonghua Yan Ke Za Zhi*. 2007;43(11):987−995.
6. Ladas JG, Siddiqui AA, Devgan U, Jun AS. A 3-D "super surface" combining modern intraocular lens formulas to generate a "super formula" and maximize accuracy. *JAMA Ophthalmol*. 2015;133(12):1431−1436.
7. Melles RB, Kane JX, Olsen T, Chang WJ. Update on intraocular lens calculation formulas. *Ophthalmology*. 2019;126(9): 1334−1335.
8. Carmona González D, Palomino Bautista C. Accuracy of a new intraocular lens power calculation method based on artificial intelligence. *Eye (Lond)*. 2021;35(2):517−522.
9. Brant AR, Hinkle J, Shi S, et al. Artificial intelligence in global ophthalmology: using machine learning to improve cataract surgery outcomes at Ethiopian outreaches. *J Cataract Refract Surg*. 2021;47(1):6−10.
10. Zisimopoulos O, Flouty E, Luengo I, et al. *DeepPhase: Surgical Phase Recognition in CATARACTS Videos*. Cham, Switzerland: Springer International Publishing; 2018: 265−272.
11. Grammatikopoulou M, Flouty E, Kadkhodamohammadi A, et al. CaDIS: cataract dataset for surgical RGB-image segmentation. *Med Image Anal*. 2021;71:102053.
12. Smith P, Tang L, Balntas V, et al. "PhacoTracking": an evolving paradigm in ophthalmic surgical training. *JAMA Ophthalmol*. 2013;131(5):659−661.
13. Neumuth T. Surgical process modeling. *Innov Surg Sci*. 2017;2(3):123−137.
14. Singh P, Aggarwal R, Tahir M, et al. A randomized controlled study to evaluate the role of video-based coaching in training laparoscopic skills. *Ann Surg*. 2015;261(5):862−869.
15. Miehle J, Ostler D, Gerstenlauer N, Minker W. The next step: intelligent digital assistance for clinical operating rooms. *Innov Surg Sci*. 2017;2(3):159−161.
16. Mamtora S, Jones R, Rabiolo A, et al. Remote supervision for simulated cataract surgery. *Eye (Lond)*. 2021:1−2.
17. Ferris JD, Donachie PH, Johnston RL, et al. Royal College of Ophthalmologists' National Ophthalmology Database study of cataract surgery: report 6. The impact of EyeSi virtual reality training on complications rates of cataract surgery performed by first and second year trainees. *Br J Ophthalmol*. 2020;104(3):324−329.
18. Jacobsen MF, Konge L, Bach-Holm D, et al. Correlation of virtual reality performance with real-life cataract surgery performance. *J Cataract Refract Surg*. 2019;45(9): 1246−1251.
19. Thomsen AS, Bach-Holm D, Kjaerbo H, et al. Operating room performance improves after proficiency-based virtual reality cataract surgery training. *Ophthalmology*. 2017;124(4):524−531.
20. Saleh GM, Wawrzynski JR, Saha K, et al. Feasibility of human factors immersive simulation training in ophthalmology: the London pilot. *JAMA Ophthalmol*. 2016;134(8):905−911.
21. Grenda TR, Pradarelli JC, Dimick JB. Using surgical video to improve technique and skill. *Ann Surg*. 2016;264(1):32−33.
22. Birkmeyer JD, Finks JF, O'Reilly A, et al. Surgical skill and complication rates after bariatric surgery. *N Engl J Med*. 2013;369(15):1434−1442.
23. Hu Y, Tiemann D, Michael Brunt L. Video self-assessment of basic suturing and knot tying skills by novice trainees. *J Surg Educ*. 2013;70(2):279−283.

24. Moore N, Yoo S, Ahmadpour N, et al. ALS-SimVR: advanced life support virtual reality training application. *25th ACM Symposium on Virtual Reality Software and Technology*. 2019: 1−2.
25. Maloca PM, Lee AY, de Carvalho ER, et al. Validation of automated artificial intelligence segmentation of optical coherence tomography images. *PloS One*. 2019;14(8): e0220063.
26. Aggoun A, Tsekleves E, Swash MR, et al. Immersive 3D holoscopic video system. *IEEE MultiMedia*. 2013;20(1): 28−37.
27. Oh R, Oh JY, Choi HJ, et al. Comparison of ocular biometric measurements in patients with cataract using three swept-source optical coherence tomography devices. *BMC Ophthalmol*. 2021;21(1):62.
28. Hao H, Zhao Y, Yan Q, et al. Angle-closure assessment in anterior segment OCT images via deep learning. *Med Image Anal*. 2021;69:101956.
29. Feussner H, Ostler D, Kohn N, et al. [Comprehensive system integration and networking in operating rooms]. *Chirurg*. 2016;87(12):1002−1007.
30. Bourcier T, Chammas J, Becmeur P-H, et al. Robot-assisted simulated cataract surgery. *J Cataract Refract Surg*. 2017;43(4):552−557.
31. Chen C-W, Lee Y-H, Gerber MJ, et al. Intraocular robotic interventional surgical system (IRISS): semi-automated OCT-guided cataract removal. *Int J Med Robot*. 2018;14(6):e1949.
32. Chammas J, Sauer A, Pizzuto J, et al. Da Vinci Xi robot-assisted penetrating keratoplasty. *Transl Vis Sci Technol*. 2017;6(3):21.
33. Tsirbas A, Mango C, Dutson E. Robotic ocular surgery. *Br J Ophthalmol*. 2007;91(1):18−21.
34. Bourcier T, Chammas J, Becmeur P-H, et al. Robotically assisted pterygium surgery: first human case. *Cornea*. 2015;34(10):1329−1330.
35. Bourcier T, Becmeur P-H, Mutter D. Robotically assisted amniotic membrane transplant surgery. *JAMA Ophthalmol*. 2015;133(2):213−214.
36. Ezzat A, Kogkas A, Holt J, et al. An eye-tracking based robotic scrub nurse: proof of concept. *Surg Endosc*. 2021;35(9): 5381−5391.
37. Noda Y, Ida Y, Tanaka S, et al. Impact of robotic assistance on precision of vitreoretinal surgical procedures. *PloS One*. 2013;8(1):e54116.
38. Xue K, Edwards TL, Meenink HCM, et al. Robot-assisted retinal surgery: overcoming human limitations. In: Ohji M, ed. *Surgical Retina*. Singapore: Springer; 2019:109−114.
39. Zhou M, Wang X, Weiss J, et al. Needle Localization for Robot-assisted Subretinal Injection based on Deep Learning, *2019 International Conference on Robotics and Automation (ICRA)*, 2019:8727−8732.
40. Hirnschall N, Amir-Asgari S, Maedel S, Findl O. Predicting the postoperative intraocular lens position using continuous intraoperative optical coherence tomography measurements. *Invest Ophthalmol Vis Sci*. 2013;54(8):5196−5203.
41. Svoboda E. Your robot surgeon will see you now. *Nature*. 2019;573(7775):S110−S111.
42. Shademan A, Decker RS, Opfermann JD, et al. Supervised autonomous robotic soft tissue surgery. *Sci Transl Med*. 2016;8(337): 337ra364.
43. Mohammadi S-F, Sabbaghi M, Z-Mehrjardi H, et al. Using artificial intelligence to predict the risk for posterior capsule opacification after phacoemulsification. *J Cataract Refract Surg*. 2012;38(3):403−408.
44. Ceschia S, Schaerf A. Modeling and solving the dynamic patient admission scheduling problem under uncertainty. *Artif Intell Med*. 2012;56(3):199−205.
45. Devi SP, Rao KS, Sangeetha SS. Prediction of surgery times and scheduling of operation theaters in ophthalmology department. *J Med Syst*. 2012;36(2):415−430.
46. National Health Service. The NHS long-term plan. Published 2021. Updated 2021. Available at: https://www.longtermplan.nhs.uk/. Accessed May 17, 2022.
47. Topol E. *Deep Medicine: How Artificial Intelligence Can Make Healthcare Human Again*. 1st ed. New York: Basic Books; 2019.
48. Topol E. *The Topol Review: Preparing the healthcare workforce to deliver the digital future; NHS Health Education.* Accessed May 17, 2022. England: NHS Health Education England; 2020. https://topol.hee.nhs.uk.
49. National Health Service. NHS X: driving forward the digital transformation of health and social care. Available at: https://www.nhsx.nhs.uk/; 2021. Accessed May 17, 2022.
50. National Health Service. NHS digital. Available at: https://digital.nhs.uk/; 2021. Accessed May 17, 2022.
51. Ophthalmologists TRCo. *National Ophthalmology Database Audit*. Royal College of Ophthalmologist; 2020:2020.
52. Wang W, Yan W, Fotis K, et al. Cataract surgical rate and socioeconomics: a global study. *Invest Ophthalmol Vis Sci*. 2016;57(14):5872−5881.
53. Global Burden of Disease 2019 Blindness and Vision Impairment Collaborators; Vision Loss Expert Group of the Global Burden of Disease Study. Causes of blindness and vision impairment in 2020 and trends over 30 years, and prevalence of avoidable blindness in relation to VISION 2020: the Right to Sight: an analysis for the Global Burden of Disease Study. *Lancet Glob Health*. 2021;9(2):e144−e160.
54. Ting DSJ, Deshmukh R, Said DG, et al. The impact of COVID-19 pandemic on ophthalmology services: are we ready for the aftermath? *Ther Adv Ophthalmol*. 2020;12.
55. The Royal College of Ophthalmologists. *The Way Forward: Cataract*. UK: The Royal College of Ophthalmologists; 2020. https://www.rcophth.ac.uk/wp-content/uploads/2021/12/RCOphth-The-Way-Forward-Cataract-300117.pdf. Accessed May 17, 2022.
56. Lin P-F, Naveed H, Eleftheriadou M, et al. Cataract service redesign in the post-COVID-19 era. *Br J Ophthalmol*. 2021;105(6):745−750.
57. Liu SK Christopher. The Royal College of Ophthalmologists. *Cataract Service during and after COVID-19 pandemic: The Royal College of Ophthalmologist focus report*. The Royal College of Ophthalmologists; 2020. https://www.rcophth.ac.uk/wp-content/uploads/2021/11/College-News-January-2021-Focus-Article.pdf. Accessed May 17, 2022.