



Artificial intelligence in pediatric surgery

Anthony Y. Tsai^{a,*}, Stewart R. Carter^b, Alicia C. Greene^a

^a Division of Pediatric Surgery, Penn State Health Children's Hospital, 500 University Drive, Hershey, PA 17033, United States

^b Division of Pediatric Surgery, University of Louisville School of Medicine, Louisville, KY, United States

ARTICLE INFO

Keywords:

Artificial intelligence
Machine learning
Natural language processing
Computer vision
Pediatric surgery
Predictive analysis

ABSTRACT

Artificial intelligence (AI) is rapidly changing the landscape of medicine and is already being utilized in conjunction with medical diagnostics and imaging analysis. We hereby explore AI applications in surgery and examine its relevance to pediatric surgery, covering its evolution, current state, and promising future. The various fields of AI are explored including machine learning and applications to predictive analytics and decision support in surgery, computer vision and image analysis in preoperative planning, image segmentation, surgical navigation, and finally, natural language processing assist in expediting clinical documentation, identification of clinical indications, quality improvement, outcome research, and other types of automated data extraction. The purpose of this review is to familiarize the pediatric surgical community with the rise of AI and highlight the ongoing advancements and challenges in its adoption, including data privacy, regulatory considerations, and the imperative for interdisciplinary collaboration. We hope this review serves as a comprehensive guide to AI's transformative influence on surgery, demonstrating its potential to enhance pediatric surgical patient outcomes, improve precision, and usher in a new era of surgical excellence.

Introduction

Artificial intelligence (AI) refers to the capability of machines or computer systems to perform tasks and make decisions that typically require human intelligence. AI systems are designed to simulate human cognitive functions such as learning, reasoning, problem-solving, perception, and language understanding.¹ They achieve this by processing large volumes of data, recognizing patterns, and using algorithms to make predictions or take actions. This is particularly useful in pediatric surgery's uniquely diverse population and needs where the power of AI can help data mine nonlinear correlations in patient data efficiently and personalize the treatment of this patient population. The marriage of AI and surgery represents a groundbreaking synergy that has the potential to redefine the landscape of medical and surgical practice.

Just as the Industrial Revolution of the 18th and 19th centuries drove one of the largest historical transformations in economic growth, technological and medical advancements, AI is poised to be the next great catalyst in societal development, increasing production efficiency, and reshaping the labor force. The integration of AI into surgical practice holds profound implications for healthcare. Surgery, once characterized solely by the dexterity of surgeons, is now a complicated orchestra of

knowledge assimilation, tactful patient work-up and diagnosis formation, skillful technical maneuvering in the operating room, and creative utilization of advanced technology. The last of which now is beginning to incorporate AI to empower surgeons with tools to make more accurate diagnoses, plan surgeries with greater precision, and execute procedures with an increasing level of accuracy.

AI's ability to process vast datasets, analyze complex medical images, and perform real-time monitoring during surgery has the potential to revolutionize the way operations including pediatric surgeries are planned and executed. It offers solutions to longstanding challenges in the field, such as reducing the risk of human error, enhancing the personalization of treatment plans, and improving patient safety.

As technology continues its relentless march forward, the incorporation of AI in pediatric surgery is not just a possibility but a burgeoning reality. We hereby explore the transformative impact of AI technology on the field of surgery and pediatric surgery, ushering in an era of precision, efficiency, and improved patient outcomes.² We will explore the historical origins of AI, different types of AI, its present applications in pediatric surgery, challenges and limitations, ethical and legal considerations, and potential future developments.

* Corresponding author.

E-mail address: atsai1@pennstatehealth.psu.edu (A.Y. Tsai).

<https://doi.org/10.1016/j.sempepsurg.2024.151390>

Available online 6 January 2024
1055-8586/© 2024 Published by Elsevier Inc.

History and evolution of AI

The intersection of AI and medicine in general is not a recent phenomenon. Its roots can be traced back to the mid-20th century when AI was described by Alan Turing in 1950.³ AI began as a simple series of “if, then rules”, or expert systems, and has advanced over several decades to include more complex algorithms that perform similarly to the human brain. There are many subfields in AI, akin to specialties in medicine, such as machine learning (ML), natural language processing (NLP), and computer vision.²

Early efforts to integrate AI into medical practice were marked by limited computational power and rudimentary algorithms. One of the pioneering applications of AI in surgery was the development of expert systems, knowledge-based systems that attempted to replicate the decision-making capabilities of human experts. The early PUMA 560 robotic arm used Classical AI and Expert Systems technology, which was prevalent during its development in the 1980s.⁴ Classical AI refers to rule-based systems and symbolic reasoning, where explicit rules and knowledge are programmed to guide the robot’s actions.⁴ While these early use cases had capabilities that were limited by the available technology of the time, they paved the way for more sophisticated AI tools.

The period between 1970 and 2000 is often referred to as the “AI winter” where reduced funding and interest led to fewer significant developments due to perceived limitations of AI and excess cost in developing and maintaining expert digital information databases.² From 2000 to the present time, the field of AI has seen rapid development powered by improved computer hardware and software as well as more readily available digitized medicine.

Chatbots exemplified the evolution of AI over the years: it evolved from the superficial communication (Eliza) of 1964 using expert systems to virtual assistants of 2010’s powered by NLP (Siri from Apple in 2011 and Alexa from Amazon in 2014) to Generative Pre-Trained Transformer 4 (GPT-4) of OpenAI using large language model and a framework of generative artificial intelligence that is much more capable than just a chatbot service.² Healthcare specific chatbots such as Pharmbot were developed in 2015 to assist in medication education for pediatric patients and their parents, and Mandy was created in 2017 as an automated patient intake process for a primary care practice.²

Development of more sophisticated algorithms in the DL branch of AI, such as convolutional neural networks (CNN), were initially limited by problems of insufficient computing capacity and lack of training data.² However, these limitations were overcome in the 2000s with the availability of larger datasets and significantly improved computing power.² CNN is a type of DL algorithm consisting of multiple layers of neural networks that automatically learn patterns, features, and representations from raw data. DL is particularly suited for tasks involving unstructured data such as images, audio, and text. It has achieved significant breakthroughs in areas like image recognition, natural language processing, and speech recognition.

Types of AI and their applications to pediatric surgery

The field of surgical AI is dynamic and continually evolving. New technologies, algorithms, and applications emerge regularly, driven by innovative research and collaboration between medical professionals and technologists. Moreover, the ongoing synergy between AI and surgery is fostering a culture of innovation and adaptation within the medical community. Surgeons are increasingly open to embracing technology as a complementary tool, ushering in an era where the fusion of human expertise and artificial intelligence augments the practice of surgery.

There are several types of AI, each with its own unique strengths and applications. We will explore the specific types of AI applications in surgery, the underlying technologies that make them possible, and the tangible benefits they bring to patients and healthcare providers alike.

Machine learning

Machine learning, a subset of AI, has become a cornerstone of AI technologies in medicine. These algorithms enable computers to learn from data and make predictions or decisions based on pattern recognition.² ML is particularly useful for identifying subtle patterns in large datasets that may be imperceptible to humans using conventional statistical analysis performing manual analyses.⁵ For instance, ML has outperformed logistic regression for the prediction of surgical site infections (SSIs) using nonlinear models that incorporate multiple data sources, including diagnoses, treatments, and laboratory values.⁶

In surgical contexts, machine learning is most often used in predictive analytics and decision support. ML algorithms have been used to analyze patient data to predict surgical outcomes, complications, and recovery times. By identifying risk factors and optimizing treatment plans, they contribute to better patient care. In the field of surgery, diagnostic and judgment errors stand as the second leading cause of preventable harm among surgical patients, after technical error.⁷ The complexity of surgical decision-making, often conducted under time constraints and amid uncertainty, can inadvertently lead to cognitive shortcuts, introducing biases, errors, and potential harm.⁸⁻¹⁰

This is where artificial intelligence steps in. ML algorithms have the capacity to learn intricate, non-linear relationships between input features and outcome labels by training on extensive repositories of electronically stored data.¹¹ Subsequently, they can generate predictions for new, previously unseen data. The true power of AI emerges when these predictions prove to be accurate, interpretable, and geared toward risk-sensitive decisions. In situations where the optimal choice is unclear and the decision has a significant impact on outcomes, AI predictions can enhance patient care.¹¹ This enhancement often takes the form of shared decision-making that aligns with patient-centered outcomes, such as short- and long-term quality of life.¹¹ Such use of AI in surgical predictive analytics has been demonstrated in preoperative risk stratification, perioperative decision-making, longitudinal surveillance and policy-making, reinforcement in surgical decision-making, among others.¹²⁻¹⁵

While work remains in validating these methods in a standardized fashion and transitioning them into the clinical environment, AI-driven predictive analytics hold immense potential to mitigate diagnostic errors, improve surgical decision-making, and ultimately enhance the quality of care provided to surgical patients.

Computer vision

Computer vision is a field of AI that focuses on enabling computers and machines to interpret, understand, and process visual information from the world, much like the human visual system. It encompasses various tasks related to visual perception and recognition, allowing machines to make sense of images and videos. Computer vision techniques have been used in radiology and surgery to train models to identify anatomical structures, instruments, and suturing motions,¹⁶ and to associate these elements with salient classifications or clinically relevant outcomes, such as surgeon case volume or technical complications. These associations can inform technical skill assessment, coaching, and performance improvement.¹⁷ Computer vision technologies are pivotal in improving the accuracy and efficiency of surgery. Here are some key aspects of AI-powered computer vision in surgery:

- **Surgical navigation:** Computer vision systems can track surgical instruments in real-time, providing precise navigation assistance to surgeons. This technology aids in maintaining optimal instrument positioning during procedures.¹⁸
- **Image segmentation:** Image segmentation is a computer vision technique that involves dividing an image into multiple segments or regions based on certain criteria or characteristics. The goal of image segmentation is to partition an image into meaningful and visually

coherent segments, where each segment corresponds to a specific object, region, or feature within the image. This process makes it easier for computer vision systems to analyze and understand the content of an image. Algorithms can segment medical images to isolate specific structures or anomalies. This is particularly valuable in procedures where precise localization is critical, such as brain and oncologic surgery. In pediatric oncological surgeries, AI algorithms are used to assist in the segmentation and identification of tumors within medical images, such as computed tomography (CT) scans, positron emission tomography (PET) scans, or magnetic resonance imaging (MRI) scans.¹⁹ These algorithms help surgeons precisely locate and visualize the extent of tumors, aiding in planning and performing tumor resections with minimal damage to healthy tissue.

- **Organ segmentation:** AI-driven image segmentation is valuable for identifying and delineating specific organs or structures within medical images. For instance, in lung, liver, or kidney surgeries, AI algorithms can segment and provide 3D reconstructions of these organs, allowing surgeons to navigate complex anatomical structures with greater accuracy.^{20–22}
- **Endoscopy and laparoscopy:** AI-based image segmentation is used in endoscopic and laparoscopic surgeries including the pediatric population. It can assist in segmenting and highlighting specific regions of interest within the endoscopic or laparoscopic video feeds, improving visibility and assisting surgeons during minimally invasive procedures. This has been demonstrated by several groups for common procedures such as laparoscopic cholecystectomy and uncommon endoscopic procedures such as peroral endoscopic myotomy (POEM) procedures.^{23–27}
- **Intraoperative navigation:** during surgery, AI can assist in segmenting and visualizing relevant structures in real-time. Surgeons can overlay this information onto their field of view using augmented reality (AR) or mixed reality (MR) systems, enhancing their ability to perform precise surgical maneuvers. This concept is an area of active research and, while it has been tested in AR-assisted transjugular intrahepatic portosystemic shunt (TIPS) procedures, actual implementation during live surgery has several challenges to overcome.^{28,29} In pediatric surgery, the feasibility of AR overlay images on a surgical patient has been tested in six patients undergoing oncological surgery.³⁰

Natural language processing

Natural language processing are algorithms that extract valuable information from unstructured medical text data, such as electronic health records and research articles. They enable efficient data retrieval, analysis, and decision support for surgeons and healthcare providers.³¹ It has revolutionized the handling of medical records and textual data in surgery. The most common use of it is the speech-to-text dictation systems for clinical documentation. NLP algorithms can also extract relevant information from large-scale database analysis such as electronic medical records (EMRs), to detect patterns in adverse events, postoperative complications, and life expectancy, allowing for more accurate and efficient record-keeping, and data mining for various trends and patterns.³² It has improved efficiency over manual extraction of databases. An example of its data mining capabilities is demonstrated in the use of NLP in a single-center EMR cohort of pediatric- and adult-onset Crohn's Disease patients that determined that biologics are associated with lower rates of surgery over time, potentially altering the natural history of the disease.³³

In addition to clinical documentation, NLP has the potential to aid with the identification of clinical conditions in preoperative, perioperative, and postoperative settings.^{34,35} Preoperatively, NLP can evaluate for surgical indications and reduce the workload of preoperative assessment.^{36,37} Perioperatively and postoperatively, NLP can help maintain continuous quality improvement efforts. NLP can identify complications and their details in unstructured free-text clinical records,

even if they are not codified with ICD-10 (*International Classification of Diseases - 10th revision*) codes.^{38,39} For example, Bucher et al. identified surgical site infections (SSIs) with an NLP pipeline that parses and extracts information from clinical notes.³⁸ The system also determined SSI subgroups based on the depth, the wound condition, and the outcome.³⁸ Furthermore, surgical outcomes can also be automatically extracted from unstructured free-text using NLP, which aids labor-intensive manual chart review.^{40,41}

NLP facilitates mining vast amounts of medical literature for insights, trends, and best practices. It aids in staying up-to-date with the latest advancements in surgical techniques and treatments.^{42,43} While publication on this use in surgery has yet to be seen, it has been demonstrated to derive insights from the COVID-19 medical literature during the pandemic where NLP has been successfully deployed to efficiently sort through the vast amounts of text-based data being continuously generated from a multitude of resources.⁴⁴

Beneficial outcomes related to AI in pediatric surgery

The incorporation of AI into pediatric surgery holds the promise of broadening the range of possibilities while also fundamentally impacting surgical practices in this field. This integration empowers surgeons to make more informed decisions, enhance procedural planning accuracy, and execute surgeries with greater precision, ultimately leading to reduced surgical risks, shorter recovery times, and improved overall outcomes for patients.

Enhanced clinical outcomes

The integration of AI into pediatric surgery can have a direct impact on patient and clinical outcomes, leading to reduced surgical risks. AI technologies, through their predictive analytics and real-time monitoring, contribute to the early identification of potential complications during the perioperative period. This proactive approach reduces the risk of adverse events. Intraoperative image segmentation by AI can help surgeons more safely navigate complex organ resections or vascular anatomy to decrease perioperative morbidity. AI-driven simulation models and AI-assisted robotic platforms can help optimize surgeon performance and reduce human error.

Machine learning algorithms can analyze patient-specific data to tailor treatment plans. This personalization optimizes outcomes and minimizes side effects, as treatments are finely tuned to each patient's unique needs. High-throughput, data-intensive biomedical research assays such as DNA sequencing, imaging protocols, and wireless health monitoring devices have resulted in problems with the analysis of vast amounts of data.⁴⁵ Statistical methods have been designed to facilitate analyses, but artificial intelligence might be more apt in dealing with 'big data' and examining the non-linear correlation of more input variables than the traditional statistics approach.⁴⁵ In the pediatric surgery population, this is particularly important as there are potentially more compounding factors that can affect a patient's outcome. Through predictive analytics and decision support, AI can play an important role in pattern recognition, health care monitoring and more reliably addressing specific care needs that a patient might have.^{45,46}

Preoperatively, AI's application in pediatric surgery includes the development of algorithms and clinical prediction tools for diagnosing and managing unique pediatric conditions.⁴⁷ As listed in Table 1, AI can assist in the risk stratification of pediatric surgical patients, diagnostic accuracy of various surgical conditions unique to the pediatric population, or in predicting postoperative complications specific to the pediatric population.⁴⁷ Through predictive analytics and decision support, AI can play an important role in pattern recognition, health care monitoring and more reliably addressing specific care needs that a pediatric patient might have.^{45,46} The integration of computer vision can enhance diagnostic accuracy and surgical planning. For example, AI-driven image analysis could significantly improve the diagnosis of

Table 1
Studies employing machine learning in the development of clinical prediction tools for pediatric surgery.⁴⁹

Author	Country of Origin	Study Type	Surgical Specialty	Condition Studied	CPT Type
Marcinkevics et al.	Germany, Switzerland	Retrospective	General	Appendicitis	Diagnostic, Prognostic, Interventional
Hu et al.	China, USA	Retrospective	General, Cardiac, Thoracic, Neurosurgery, Cranioplasty, Gynecological, Plastic, Other	Neonatal postoperative mortality	Prognostic
Lure et al.	USA	Retrospective	General	Necrotizing enterocolitis, spontaneous intestinal perforation	Diagnostic
Stiel et al.	Germany	Retrospective	General	Appendicitis	Diagnostic
Troesch et al.	USA	Retrospective	Urology	Febrile breakthrough urinary tract infection within 13 months of starting prophylactic antibiotics in children with vesicoureteral reflux	Prognostic
Cooper et al.	USA	Retrospective	General, Thoracic, Otolaryngology, Orthopedic, Urology, Neurosurgery, Plastic	30-day surgical morbidity	Prognostic
Chen et al.	Canada, Singapore	Retrospective	Cardiac	Infants listed for heart transplantation who would survive at least 3 months post-transplantation	Prognostic
Lorenzo et al.	Canada	Prospective	Urology	Infants who are most likely to undergo a surgical intervention for prenatal hydronephrosis	Interventional
Ward et al.	USA	Retrospective	Anesthesiology	Prolonged opioid use after surgery in adolescents	Prognostic
Zhang et al.	China	Retrospective	Ophthalmology	Postoperative complications of pediatric cataract patients within 1 year after surgery	Prognostic
Jalali et al.	USA	Prospective	Cardiac	Occurrence of periventricular leukomalacia in neonates post-cardiac surgery	Prognostic
Jalali et al.	USA	Retrospective	Cardiac	Occurrence of periventricular leukomalacia in neonates post-cardiac surgery	Prognostic
Miller et al.	USA	Retrospective	Transplant	Predicting mortality post-transplant surgery within 1, 3 or 5 years	Prognostic
Sun et al.	China	Retrospective	Cardiac	Arrhythmia after interventional closure in children with atrial septal defect	Prognostic
Wilson et al.	USA	Retrospective	Neurosurgery	Persistent neonatal brachial plexus palsy patients that would benefit from surgery	Interventional
Habibi et al.	Iran	Retrospective	Neurosurgery	Ventriculoperitoneal shunt infection in children with hydrocephalus	Prognostic
Guo et al.	China	Retrospective	Cardiac	Postoperative blood coagulation state of children with congenital heart disease	Prognostic
Bertoni et al.	USA	Retrospective	Otolaryngology	Children needing postoperative overnight monitoring based on the polysomnographic severity of obstructive sleep disordered breathing	Interventional
Wadhvani et al.	Canada, USA	Prospective	Transplant	Ideal outcome at 3 years post-liver transplant	Prognostic
Azimi et al.	Iran	Retrospective	Neurosurgery	Endoscopic third ventriculostomy success at 6 months	Prognostic
Skoch et al.	USA	Retrospective	Neurosurgery	Symptomatic cerebral vasospasm in children with aneurysmal subarachnoid haemorrhage	Prognostic
Cooper et al.	USA	Retrospective	General/Thoracic, Otolaryngology, Orthopedic, Urology, Neurosurgery, Plastic	Postoperative neonatal mortality	Prognostic
Cohen et al.	USA	Retrospective	Neurosurgery	Candidates for pediatric epilepsy surgery	Interventional
Pasha et al.	USA	Retrospective	Orthopedic	3D global spinal alignment 2 years after posterior fusion spinal surgery in patients with adolescent idiopathic scoliosis	Prognostic
Hale et al.	Canada, USA	Prospective	Neurosurgery	Cerebrospinal fluid shunt failure	Prognostic
Killian et al.	USA	Retrospective	Transplant	Post-transplant hospitalization	Prognostic
Wissel et al.	USA	Retrospective	Neurosurgery	Candidates for epilepsy surgery	Interventional
Saltzman et al.	USA	Retrospective	Urology	Candidates for venous access placement	Interventional
Bertsimas et al.	Greece, Poland, Portugal, USA	Retrospective	Cardiac	Adverse outcomes for congenital heart surgery	Prognostic
Avila-George et al.	Peru	Retrospective	General	Discharge diagnosis in surgical patients	Diagnostic
Ruiz-Fernandez et al.	Colombia, Spain	Retrospective	Cardiac	Risk in congenital heart surgery	Risk Stratifying
Reddan et al.	Australia	Prospective, Retrospective	General	Acute appendicitis	Diagnostic
Aydin et al.	Turkey	Retrospective	General	Acute appendicitis	Diagnostic
Lin et al.	China	Retrospective	Ophthalmology	Congenital cataracts	Diagnostic
Shahi et al.	USA	Retrospective	Trauma	Need for massive transfusion, failure of non-operative management, mortality, and successful non-operative management without intervention in the setting of blunt solid organ injury	Interventional
Dong et al.	China	Retrospective	General	Biliary atresia	Diagnostic
DiRusso et al.	USA	Retrospective	Trauma	Survival	Prognostic
Guo et al.	China	Retrospective	Neurosurgery	Focal cortical dysplasia, glioneuronal tumours	Diagnostic
Liu et al.	China	Retrospective	General	Biliary atresia	Diagnostic

(continued on next page)

Table 1 (continued)

Author	Country of Origin	Study Type	Surgical Specialty	Condition Studied	CPT Type
Ruiz et al.	USA	Retrospective	Cardiac	Critical events in infants with single-ventricle physiology before second-stage surgery	Risk stratifying
Bartz-Kurycki et al.	USA	Retrospective	General	Surgical site infection	Prognostic
Jamshidnezhad et al.	Iran	Retrospective	General	Appendicitis	Diagnostic
Schwartz et al.	USA	Retrospective	Orthopedic	Surgical indications for femoral derotational osteotomy	Interventional
Grundmeier et al.	USA	Prospective	General	Surgical site infection	Prognostic
Chang Junior et al.	Brazil	Retrospective	Cardiac	Mortality among patients with congenital heart disease undergoing cardiac surgery	Prognostic
Peltri et al.	Germany	Retrospective	Cardiac	Postoperative effusion and edema	Prognostic
Hale et al.	USA	Retrospective	Neurosurgery	6-month outcomes in pediatric patients sustaining traumatic brain injury	Prognostic
Jalali et al.	USA	Prospective	Craniofacial	Blood transfusion requirement	Interventional

Abbreviations: CPT, Clinical Prediction Tool; USA, United States of America.

pediatric conditions from imaging studies; there are already 3 commercially available bone-age assessment AI tools,⁴⁸ and as of 2021, there were already 100 different AI software products for radiologists on the market with variable supporting evidence.⁴⁹

Intraoperatively, instruments and technologies continue to develop for pediatric surgery, computer vision and other AI algorithms can enhance pediatric surgeons' ability to perform intricate procedures with improved precision. Specifically, for robotics, the stability and steadiness of the robotic systems reduce the margin for error, minimizing damage to surrounding tissues. Surgical robots could utilize machine learning and surgical navigation to not only enhance the operator but improve ergonomics through the use of Ergonomic assessment AI software.⁵⁰ The Intuitive Surgical® SureForm stapler, which is used in conjunction with the da Vinci platform, is an example of a smart tool that takes tissue density into account and adjusts that staple fire based on needed thickness.⁵¹ While this type of smart tool is already being employed, the future could see robots anticipating needed instruments based on pattern recognition of tissue types and specific operations. Intraoperative AI guidance can help decrease operative time, bleeding, and errors that can contribute to longer hospitalizations. Additionally, minimally invasive robotic procedures often result in shorter recovery times, less pain, and reduced postoperative discomfort for patients.

Postoperatively, the development of wireless sensors and AI-driven remote monitoring devices can also allow healthcare providers to keep a close eye on pediatric surgery patients' progress, providing timely interventions when necessary.⁵² The potential for analysis of large amounts of monitored data points and identification of early warning signs by AI could help alert providers of potential complications, prevent readmissions, reoperation, and save health care dollars. Finally, as previously discussed, NLP can be used to maintain continuous quality improvement efforts by identifying complications and their details.³⁸

Reduced surgical costs

While the initial investment in AI technology for surgery can be substantial, the long-term benefits could translate into cost reductions realized through fewer complications and optimized resource utilization through quality improvement projects examining the multitude of factors affecting different quality measures. Surgical complication reduction can translate into fewer hospital readmissions and re-interventions, thereby saving healthcare costs. Optimized resource allocation from surgical equipment and operating room time to staff allocation, can reduce waste and improve efficiency.

Increased efficiency

The incorporation of AI technologies can streamline various aspects of surgical practice including faster decision-making through real-time

data analysis and decision support systems to help pediatric surgeons make quicker and more informed decisions during surgery. AI-driven tools, such as robotic systems, can improve surgical workflow by automating repetitive tasks, allowing surgeons to focus on critical aspects of the procedure. Machine learning and computer vision have the potential to make pediatric surgeons more efficient in minimally invasive surgeries or through AR/MR technology, allowing them to focus, and potentially assisting with overlapped preoperative imaging, on critical aspects of the operation. As technology allows audiovisual data storage easier and more accessible, AI-assisted annotation, segmentation, and analysis will make it a useful tool in helping surgeons hone their skills and improve future outcomes.

Challenges and limitations

While AI offers promising advancements, it's crucial to acknowledge its limitations, especially in the context of pediatric surgery. The strength of AI is its ability to uncover subtle patterns in data. However, in order for the method to be successful, it requires a large database that is representative of the general population and each input is labeled or annotated correctly. The outputs of the AI analyses are limited by the types and accuracy of available data. Systematic biases in clinical data collection can affect the type of pattern AI recognizes or the predictions it may make. Pediatric data sets may have unique biases or limitations, given the smaller patient population and the diversity of developmental stages. In addition, the interpretability of AI algorithms is a significant concern, as pediatric surgeons need to understand the basis of AI-driven recommendations for techniques such as neural networks are based on a "black box" design where how or why such patterns were discerned by the computer is essentially unknown.¹⁹ Therefore, the accountability of these algorithms, the safety/verifiability of automated analyses, and the implications of these analyses on human-machine interactions can impact the utility of AI in clinical practice.⁵³ As the computer science community works to improve the interpretability of AI analyses, we as pediatric surgeons must have early input in the design of AI algorithms to improve the accountability and interpretability of big data analyses.⁵⁴

In addition to the challenges of AI technology, the collection, storage, and analysis of patient data, particularly sensitive medical information, must adhere to strict privacy regulations, such as Health Insurance Portability and Accountability Act (HIPAA) in the United States and General Data Protection Regulation (GDPR) in Europe. Ensuring patient data confidentiality is paramount. Pre-existing regulations are inadequate to address a rapidly developing field such as AI. Specific laws and regulations are currently being developed around the world to address issues pertaining to this new technology. In addition, as AI systems rely on interconnected networks and databases, they become vulnerable to cyberattacks. Safeguarding against data breaches and unauthorized access to AI-driven surgical tools and patient records is an ongoing

concern. The ability to de-identify or anonymize patient health data may be compromised in light of new algorithms that have successfully re-identified such data.⁵⁵

Legal and ethical considerations

Liability and legal issues

The integration of AI into pediatric surgery introduces complex issues regarding liability and legal responsibility. When an AI algorithm potentially makes an incorrect diagnosis or treatment recommendation, it raises critical questions about legal accountability. Determining whether the surgeon, the hospital, or the AI developer is responsible necessitates the establishment of clear guidelines and liability frameworks. Additionally, ensuring regulatory compliance for AI applications in healthcare is both essential and challenging. AI systems in pediatric surgery must undergo rigorous testing and validation to meet regulatory standards and gain approval. This process can be particularly difficult to keep pace with given the rapid advancements in AI technology. As such, the healthcare sector must navigate these legal and regulatory landscapes carefully to effectively integrate AI into pediatric surgery.

Ethical considerations in decision making

AI technologies hold the potential to significantly assist surgeons in decision-making processes, yet their integration into healthcare raises several ethical concerns. Firstly, transparency and accountability are paramount; surgeons need to fully understand and trust the recommendations provided by AI algorithms. These algorithms should offer transparent explanations for their decisions, ensuring that surgeons retain control over patient care. Although it is impractical to make the extensive training data of AI available for every user to assess reliability and bias, developers and decision-makers are encouraged to disclose the values and standards incorporated into AI programming.⁵⁵ This step is crucial to preserve the essential role of bedside assessment and human intuition in the decision-making process. In instances where there is a discrepancy between a clinician's judgment and AI recommendations, obtaining a second human opinion is advised to maintain accountability and transparency.⁵⁶

Another critical issue is the potential for bias and fairness in AI. Since AI relies on historical data, which may be inherently biased due to past data generation methods or clinical practices, biases in training data can influence AI algorithms, potentially leading to disparities in patient care.¹¹ Addressing this challenge involves strategically deploying AI and carefully selecting data for algorithm development to mitigate biases and ensure fairness in AI decision-making.⁵⁷ Furthermore, patient autonomy and informed consent are essential ethical considerations. Patients have the right to make informed decisions about their care, and this extends to treatments involving AI. Patients must be informed about the role and limitations of AI in their treatment planning, ensuring they understand how AI influences their care and maintaining their right to informed consent. Overall, while AI offers substantial benefits in surgical decision-making, addressing these ethical concerns is crucial for its responsible and patient-centered application in healthcare.

AI holds tremendous potential to revolutionize pediatric surgery, enhancing both clinical care and surgical education. However, its successful integration requires careful consideration of the unique aspects of pediatric surgery, active involvement of surgeons in AI development, navigation of ethical and regulatory considerations, and a focus on patient and family engagement. With these considerations, AI can significantly contribute to advancing pediatric surgical care, ensuring the highest quality of treatment for young patients.

Future implications for practice

In the context of the future directions of AI in pediatric surgery,

surgical robots like the da Vinci Surgical System, while not inherently AI, incorporate AI algorithms, such as tremor control, to enhance precision in various minimally invasive procedures across specialties. Competing systems in pediatric surgery, including those from Asensus Surgical, also integrate AI into their consoles for improved surgical decision-making.⁵⁸ As we envision the future of AI in pediatric surgery, the increasing technical complexity of robotic surgeries necessitates advanced training models for proficiency.^{59,60} The incorporation of AI, particularly machine learning algorithms, holds great promise for enhancing technical skill assessment by integrating motion analysis, energy, and force usage, making it more objective, automated, and efficient.^{61–64} Ongoing research aims to develop autonomous surgical robots capable of independent task performance, thereby reducing surgeon workload and further improving procedural accuracy.⁶⁵

Additionally, the advancements in telemedicine combined with AI-powered robotic systems can bring much needed pediatric surgery expertise to remote or underserved areas. The first remote surgical procedure, a robotic cholecystectomy, performed in 2001 from New York to Strasbourg, France demonstrated that such capability is possible.⁶⁶ A major flaw noted during remote surgical procedures is latency times that can prolong procedures and result in significant surgical inaccuracies,⁶⁶ but AI has the ability to address these problems. This convergence of AI and robotic surgery opens new avenues for advancing pediatric surgical care.

Lastly, although the use of AI applications has expanded for diagnosing and clinically managing pediatric surgical patients, its intraoperative applications remain limited. Lo Muzio et al. showed how employing video and machine learning models during an open operation for congenital heart defects enabled real-time assessment of epicardial kinematics, facilitating medical decisions prior to chest closure.⁶⁷ This example illustrates how AI applications like these have the potential to further extend the utilization of intraoperative AI in the future, contributing to enhanced decision-making and surgical outcomes in the field of pediatric surgery.

Conclusions

In summary, the integration of AI into pediatric surgery heralds a transformative era, offering improved diagnostic accuracy, surgical precision, and enhanced patient outcomes. However, challenges such as ethical considerations and the need for regulatory frameworks underscore the necessity for careful navigation of this evolving landscape.

References

1. Hamet P, Tremblay J. Artificial intelligence in medicine. *Metabolism*. 2017;69s: S36–s40.
2. Kaul V, Enslin S, Gross SA. History of artificial intelligence in medicine. *Gastrointest Endosc*. 2020;92:807–812.
3. Ramesh AN, Kambhampati C, Monson JR, Drew PJ. Artificial intelligence in medicine. *Ann R Coll Surg Engl*. 2004;86:334–338.
4. Piltan F, Haghighi ST, Sulaiman N, Nazari I, Siamak S. Artificial control of PUMA robot manipulator: a-review of fuzzy inference engine and application to classical controller. *Int J Robot Autom*. 2011;2:401–425.
5. Cruz JA, Wishart DS. Applications of machine learning in cancer prediction and prognosis. *Cancer Inform*. 2007;2:59–77.
6. Soguero-Ruiz C, Fei WM, Jenssen R, et al. Data-driven temporal prediction of surgical site infection. In: *Proceedings of the AMIA Annual Symposium*. 2015. 2015: 1164–1173.
7. Healey MA, Shackford SR, Osler TM, Rogers FB, Burns E. Complications in surgical patients. *Arch Surg*. 2002;137:611–617. discussion 617–618.
8. Shanafelt TD, Balch CM, Bechamps G, et al. Burnout and medical errors among American surgeons. *Ann Surg*. 2010;251:995–1000.
9. Gropman JE, Prichard M. *How Doctors Think*. Houghton Mifflin Boston; 2007.
10. Wolf FM, Gruppen LD, Billi JE. Differential diagnosis and the competing-hypotheses heuristic. A practical approach to judgment under uncertainty and Bayesian probability. *JAMA*. 1985;253:2858–2862.
11. Loftus TJ, Tighe PJ, Filiberto AC, et al. Artificial intelligence and surgical decision-making. *JAMA Surg*. 2020;155:148–158.
12. El Hechi MW, Nour Eddine SA, Maurer LR, Kaafarani HMA. Leveraging interpretable machine learning algorithms to predict postoperative patient outcomes on mobile devices. *Surgery*. 2021;169:750–754.

13. Brennan M, Hagan JD, Giordano C, et al. Multiobjective optimization challenges in perioperative anesthesia: a review. *Surgery*. 2021;170:320–324.
14. Eyler Dang L, Hubbard A, Dissak-Delon FN, Chichom Mefire A, Juillard C. Right population, right resources, right algorithm: Using machine learning efficiently and effectively in surgical systems where data are a limited resource. *Surgery*. 2021;170:325–328.
15. Datta S, Li Y, Ruppert MM, et al. Reinforcement learning in surgery. *Surgery*. 2021;170:329–332.
16. Esteva A, Robicquet A, Ramsundar B, et al. A guide to deep learning in healthcare. *Nat Med*. 2019;25:24–29.
17. Rogers MP, DeSantis AJ, Janjua H, Barry TM, Kuo PC. The future surgical training paradigm: virtual reality and machine learning in surgical education. *Surgery*. 2021;169:1250–1252.
18. Ward TM, Mascagni P, Ban Y, et al. Computer vision in surgery. *Surgery*. 2021;169:1253–1256.
19. Huang J, Shlobin NA, Lam SK, DeCuyper M. Artificial intelligence applications in pediatric brain tumor imaging: a systematic review. *World Neurosurg*. 2022;157:99–105.
20. Zheng Z, Ren M, Li B, et al. Application value of artificial intelligence-assisted three-dimensional reconstruction in planning thoracoscopic segmentectomy. *Zhongguo Fei Ai Za Zhi*. 2023;26:515–522.
21. Takamoto T, Ban D, Nara S, et al. Automated three-dimensional liver reconstruction with artificial intelligence for virtual hepatectomy. *J Gastrointest Surg*. 2022;26:2119–2127.
22. Di Dio M, Barbuto S, Biseogna C, et al. Artificial intelligence-based hyper accuracy three-dimensional (HA3D®) models in surgical planning of challenging robotic nephron-sparing surgery: a case report and snapshot of the state-of-the-art with possible future implications. *Diagnostics*. 2023;13(14):2320.
23. Madani A, Namazi B, Altieri MS, et al. Artificial intelligence for intraoperative guidance: using semantic segmentation to identify surgical anatomy during laparoscopic cholecystectomy. *Ann Surg*. 2022;276:363–369.
24. Hegde SR, Namazi B, Iyengar N, et al. Automated segmentation of phases, steps, and tasks in laparoscopic cholecystectomy using deep learning. *Surg Endosc*. 2024;38(1):158–170.
25. Golany T, Aides A, Freedman D, et al. Artificial intelligence for phase recognition in complex laparoscopic cholecystectomy. *Surg Endosc*. 2022;36:9215–9223.
26. Nakanuma H, Endo Y, Fujinaga A, et al. An intraoperative artificial intelligence system identifying anatomical landmarks for laparoscopic cholecystectomy: a prospective clinical feasibility trial (J-SUMMIT-C-01). *Surg Endosc*. 2023;37:1933–1942.
27. Ward TM, Hashimoto DA, Ban Y, et al. Automated operative phase identification in peroral endoscopic myotomy. *Surg Endosc*. 2021;35:4008–4015.
28. Yang J, Zhu J, Sze DY, et al. Feasibility of augmented reality-guided transjugular intrahepatic portosystemic shunt. *J Vasc Interv Radiol*. 2020;31:2098–2103.
29. Unberath M, Gao C, Hu Y, et al. The impact of machine learning on 2D/3D registration for image-guided interventions: a systematic review and perspective. *Front Robot AI*. 2021;8:716007.
30. Souzaki R, Ieiri S, Uemura M, et al. An augmented reality navigation system for pediatric oncologic surgery based on preoperative CT and MRI images. *J Pediatr Surg*. 2013;48:2479–2483.
31. Kreimeyer K, Foster M, Pandey A, et al. Natural language processing systems for capturing and standardizing unstructured clinical information: a systematic review. *J Biomed Inform*. 2017;73:14–29.
32. Weegar R. Applying natural language processing to electronic medical records for estimating healthy life expectancy. *Lancet Reg Health West Pac*. 2021;9:100132.
33. Kurowski JA, Milinovich A, Ji X, et al. Differences in biologic utilization and surgery rates in pediatric and adult crohn's disease: results from a large electronic medical record-derived cohort. *Inflamm Bowel Dis*. 2021;27:1035–1044.
34. Mellia JA, Basta MN, Toyoda Y, et al. Natural language processing in surgery: a systematic review and meta-analysis. *Ann Surg*. 2021;273:900–908.
35. Wyatt JM, Booth GJ, Goldman AH. Natural language processing and its use in orthopaedic research. *Curr Rev Musculoskelet Med*. 2021;14:392–396.
36. Wissel BD, Greiner HM, Glauser TA, et al. Prospective validation of a machine learning model that uses provider notes to identify candidates for resective epilepsy surgery. *Epilepsia*. 2020;61:39–48.
37. Fonferko-Shadrach B, Lacey AS, Roberts A, et al. Using natural language processing to extract structured epilepsy data from unstructured clinic letters: development and validation of the ExECT (extraction of epilepsy clinical text) system. *BMJ Open*. 2019;9:e023232.
38. Bucher BT, Shi J, Ferraro JP, et al. Portable automated surveillance of surgical site infections using natural language processing: development and validation. *Ann Surg*. 2020;272:629–636.
39. Selby LV, Narain WR, Russo A, Strong VE, Stetson P. Autonomous detection, grading, and reporting of postoperative complications using natural language processing. *Surgery*. 2018;164:1300–1305.
40. Borjali A, Magnéli M, Shin D, Malchau H, Muratoglu OK, Varadarajan KM. Natural language processing with deep learning for medical adverse event detection from free-text medical narratives: a case study of detecting total hip replacement dislocation. *Comput Biol Med*. 2021;129, 104140.
41. Tibbo ME, Wyles CC, Fu S, et al. Use of natural language processing tools to identify and classify periprosthetic femur fractures. *J Arthroplasty*. 2019;34:2216–2219.
42. Kang T, Sun Y, Kim JH, et al. EvidenceMap: a three-level knowledge representation for medical evidence computation and comprehension. *J Am Med Inform Assoc*. 2023;30:1022–1031.
43. Yang X, Chen A, PourNejatian N, et al. A large language model for electronic health records. *npj Digit Med*. 2022;5:194.
44. Reddy S, Bhaskar R, Padmanabhan S, et al. Use and validation of text mining and cluster algorithms to derive insights from Corona Virus disease-2019 (COVID-19) medical literature. *Comput Methods Progr Biomed Update*. 2021;1, 100010.
45. Schork NJ. Artificial intelligence and personalized medicine. *Cancer Treat Res*. 2019;178:265–283.
46. Vashistha R, Dangi AK, Kumar A, Chhabra D, Shukla P. Futuristic biosensors for cardiac health care: an artificial intelligence approach. *3 Biotech*. 2018;8:358.
47. Bianco A, Al-Azzawi ZAM, Guadagno E, Osmanliu E, Gravel J, Poenaru D. Use of machine learning in pediatric surgical clinical prediction tools: a systematic review. *J Pediatr Surg*. 2023;58:908–916.
48. Offiah AC. Current and emerging artificial intelligence applications for pediatric musculoskeletal radiology. *Pediatr Radiol*. 2022;52:2149–2158.
49. van Leeuwen KG, Schalekamp S, Rutten M, van Ginneken B, de Rooij M. Artificial intelligence in radiology: 100 commercially available products and their scientific evidence. *Eur Radiol*. 2021;31:3797–3804.
50. Hamilton BC, Dairywala MI, Hightet A, et al. Artificial intelligence based real-time video ergonomic assessment and training improves resident ergonomics. *Am J Surg*. 2023;226:741–746.
51. SureForm Staplers: intuitive. <https://www.intuitive.com/en-us/products-and-services/da-vinci/stapling/sureform>. Accessed November 12, 2023.
52. De Boer C, Ghomrawi H, Many B, et al. Utility of wearable sensors to assess postoperative recovery in pediatric patients after appendectomy. *J Surg Res*. 2021;263:160–166.
53. Cabitza F, Rasoini R, Gensini GF. Unintended consequences of machine learning in medicine. *JAMA*. 2017;318:517–518.
54. Hashimoto DA, Rosman G, Rus D, Meireles OR. Artificial intelligence in surgery: promises and perils. *Ann Surg*. 2018;268:70–76.
55. Murdoch B. Privacy and artificial intelligence: challenges for protecting health information in a new era. *BMC Med Ethics*. 2021;22:122.
56. Kempt H, Nagel SK. Responsibility, second opinions and peer-disagreement: ethical and epistemological challenges of using AI in clinical diagnostic contexts. *J Med Ethics*. 2022;48:222–229.
57. Parikh RB, Teeple S, Navathe AS. Addressing bias in artificial intelligence in health care. *JAMA*. 2019;322:2377–2378.
58. Staib L, Poth C, Schilcher F, et al. Safety in senhance™ robotic gastrointestinal surgery in 530 patients. *Surg Technol Int*. 2023;42, sti42/1662.
59. Satava RM, Stefanidis D, Levy JS, et al. Proving the effectiveness of the fundamentals of robotic surgery (FRS) skills curriculum: a single-blinded, multispecialty, multi-institutional randomized control trial. *Ann Surg*. 2020;272:384–392.
60. Mascheroni J, Stockburger M, Patwala A, et al. Effect of metrics-based simulation training to proficiency on procedure quality and errors among novice cardiac device implanters: the IMPROF randomized trial. *JAMA Netw Open*. 2023;6, e2322750.
61. Pedrett R, Mascagni P, Beldi G, Padoy N, Lavanchy JL. Technical skill assessment in minimally invasive surgery using artificial intelligence: a systematic review. *Surg Endosc*. 2023;37:7412–7424.
62. Fard MJ, Ameri S, Darin Ellis R, Chinnam RB, Pandya AK, Klein MD. Automated robot-assisted surgical skill evaluation: predictive analytics approach. *Int J Med Robot*. 2018;14(1):1850.
63. Wang Z, Majewicz Fey A. Deep learning with convolutional neural network for objective skill evaluation in robot-assisted surgery. *Int J Comput Assist Radiol Surg*. 2018;13:1959–1970.
64. Ershad M, Rege R, Majewicz Fey A. Automatic and near real-time stylistic behavior assessment in robotic surgery. *Int J Comput Assist Radiol Surg*. 2019;14:635–643.
65. Kurzweil R. *The Singularity is Near: When Humans Transcend Biology*. Viking; 2005.
66. Choi PJ, Oskouian RJ, Tubbs RS. Telesurgery: past, present, and future. *Cureus*. 2018;10:e2716.
67. Lo Muzio FP, Rozzi G, Rossi S, et al. Artificial intelligence supports decision making during open-chest surgery of rare congenital heart defects. *J Clin Med*. 2021;10(22):5330.