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Aashim Bhatia, Farzad Khalvati and Birgit Betina Ertl-Wagner

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STATE OF PRACTICE

Artificial Intelligence in the Future Landscape of Pediatric Neuroradiology: Opportunities and Challenges

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ABSTRACT

SUMMARY: This paper will review how artificial intelligence (AI) will play an increasingly important role in pediatric neuroradiology in the future. A safe, transparent, and human-centric AI is needed to tackle the quadruple aim of improved health outcomes, enhanced patient and family experience, reduced costs, and improved well-being of the healthcare team in pediatric neuroradiology. Equity, diversity and inclusion, data safety, and access to care will need to always be considered. In the next decade, AI algorithms are expected to play an increasingly important role in access to care, workflow management, abnormality detection, classification, response prediction, prognostication, report generation, as well as in the patient and family experience in pediatric neuroradiology. Also, AI algorithms will likely play a role in recognizing and flagging rare diseases and in pattern recognition to identify previously unknown disorders. While AI algorithms will play an important role, humans will not only need to be in the loop, but in the center of pediatric neuroimaging. AI development and deployment will need to be closely watched and monitored by experts in the field. Patient and data safety need to be at the forefront, and the risks of a dependency on technology will need to be contained. The applications and implications of AI in pediatric neuroradiology will differ from adult neuroradiology.

ABBREVIATIONS: AI = artificial intelligence; LLM = large language models

"It is difficult to make predictions, especially about the future." This quote has been attributed to many different people, most popularly to Mark Twain and Yogi Berra. There have been methodologic leaps in the evolution of artificial intelligence (AI) that have not been foreseen, even by experts in the field.[1] One of the most recent examples is the rapid development and unprecedented impact of ChatGPT and other large language models (LLMs), the success of which had not been foreseen, at least not at that time and to that extent. A search with the key word "ChatGPT" on PubMed on August 18, 2023, rendered 4 publications in 2022 and 1046 publications in 2023 to date.[2] LLMs are currently causing major discussions on the future of medical scientific publishing.[3] Of note, this article has not been written with the help of LLMs, such as ChatGPT.

ChatGPT produces references that are fake and may initially appear legitimate. A significant amount of time can be spent to search for these falsified articles.[4] This provides an opportunity to teach LLM what is a true reference and an example of continued learning of the LLM, which requires human intervention. An author of this paper had a similar experience with ChatGPT3; it needs to be noted that ChatGPT4 has been released and is more advanced with fewer errors.

There is general agreement that AI will positively influence the field of radiology. This has evolved from an initial fear that radiologists would be replaced by AI to a more nuanced understanding and embracing of the methodology.[5] The influence of AI on the field of pediatric neuroradiology will be different from its impact on general radiology and even different from its impact on adult neuroradiology, where advances are being made especially in disorders with a high disease prevalence such as stroke.[6,7] There are several reasons for this, included in the Table.

Currently, only a relatively small percentage of neuroradiologists spend 100% of their clinical time on pediatric neuroradiology. The impact of AI software customized to pediatric neuroradiology will affect a smaller pool of neuroradiologists compared with software focused on adult pathologies, such as neurodegenerative diseases, and there is less commercial interest from companies to develop software dedicated to pediatric neuroradiology. However, the impact on healthcare outcomes can be highly relevant, especially in settings in which there is only limited pediatric neuroradiology expertise.

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From the Children's Hospital of Philadelphia (A.B.), Philadelphia, Pennsylvania; and Hospital for Sick Children (F.K., B.B.E.-W.), Toronto, Ontario, Canada.

Please address correspondence to Aashim Bhatia, MD, Children's Hospital of Philadelphia, Department of Radiology, Division of Neuroradiology, 3500 Civic Center Blvd, Office 2592, Philadelphia, PA 19104; e-mail: aashimbhatia@gmail.com

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Reasons for a differing impact of artificial intelligence on pediatric neuroradiology compared with adult neuroradiology

- Lower number of pediatric neuroradiologists
- High degree of subspecialization
- Rapid evolution of the field with an evolving understanding of the molecular and genetic underpinnings of disorders
- Wide spectrum of neurologic disorders in the pediatric age range
- Differing neuroimaging manifestations of disorders depending on age
- Small sample sizes of rare neuropediatric disorders, especially when considering subcategories/molecular subtypes
- More rare and orphan diseases in the pediatric age range
- Rapid evolution of targeted therapeutic approaches for precision child health

We strongly believe that AI in pediatric neuroradiology not only requires a "human in the loop," but humans in the center.[8] AI in pediatric neuroradiology needs to be patient-centered, family-centered, and physician/pediatric neuroradiologist-centered. AI in pediatric neuroradiology needs to be centered around the quadruple aim in health care, which encompasses[9]:

- improvement of health outcomes
- enhancement of the patient and family experience
- reduction of costs
- improvement of well-being of the health care team.

All these aims need to be based on the principles of equity, diversity, and inclusivity, and access to care needs to be a global consideration. The American College of Radiology has published on the safe, reliable, and effective use of AI in children.[10]

AI can and will help to achieve the quadruple aim in pediatric neuroradiology, but the development and deployment of its algorithms will need to be closely watched and monitored by experts in the field. Patient and data safety need to be at the forefront of all endeavors, and it will need to be ascertained that the risks of a dependency on technology will be contained.

AI algorithms will play an increasingly important role in access to care, workflow management, abnormality detection, classification, response prediction, prognostication, and report generation, as well as in the patient and family experience in pediatric neuroradiology in the years to come. The human aspect of pediatric neuroradiology will remain central, with a pediatric neuroradiologist being key to imaging interpretation. Pediatric patients currently require imaging at record high numbers due to improved imaging capabilities for diagnosis, and assessing and predicting treatment responses and this is likely to further increase in the future. More advanced imaging techniques, such as 7T MR imaging, chemical exchange saturation transfer, sodium MR imaging, and PET, will likely play an increasing role in the future, warranting the development of algorithms tailored to pediatric patients. Decreasing image acquisition times will allow for higher number of patients being examined. At the same time, the current shortage of radiologists qualified to interpret pediatric neuroradiology is not likely to reverse anytime soon and the strain on already challenged pediatric neuroradiology divisions is bound to increase (Online Supplemental Data).

Access to Pediatric Neuroimaging Care

On a global level, access to pediatric neuroimaging care is limited and we will need to increase our efforts to improve equitable access. Reasons for these limitations in access are manifold and opportunities for AI to support are centered along various lines (Online Supplemental Data).

Workflow Management

Workflow management in pediatric neuroradiology is very complex as it requires a balancing of priorities in an often resource-restricted environment, a judicious use of various imaging modalities and image-guided treatment approaches, and differing needs for emergency patients, inpatients, and outpatients. In addition, the requirement for sedation depending on the age and developmental stage of the patient and type of imaging examination or intervention adds a further layer of complexity as it requires coordination between various services, including anesthesiology, nursing, and pediatric neuroradiology, and risk levels need to be considered.[11] Often, several imaging examinations are combined under a single sedation. Traditionally, workflow management, including scheduling and rostering in pediatric neuroradiology, is largely dependent on humans often in interaction with dedicated software systems. AI algorithms can help facilitate workflow management in pediatric neuroradiology from various perspectives:

- Clinical decision support: AI-based clinical decision support systems can be trained on available demographic information and clinical data, to help in deciding whether imaging should be performed at all, in which timeframe it should be performed, and which imaging modality is best suited for the clinical indication in pediatric neuroradiology.
- Prioritization of examinations: AI algorithms can aid in prioritizing pediatric neuroimaging examinations according to urgency. This is especially important for situations in which there are long waitlists for imaging examinations and in which more urgent examination requests need to be scheduled for imaging, for example, based on ordering request details such as stat priority, history, neurologic status, and/or electronic medical record.
- Scanner and protocol selection: Based on the ordering comments and/or information from the electronic medical record, AI algorithms can help select the optimal scanner and imaging protocol for the individual patient's indication.
- Scheduling: AI algorithms can help to optimally schedule patient examinations based on various criteria, including availability of a specific imaging modality and pediatric neuroradiologist, child life services, and/or pediatric anesthesiologist, as well as patient and family preferences.[12] They can help to ascertain that imaging examinations are optimally combined, which is especially important when sedation is needed.[13] AI-assisted scheduling can also help in ensuring equitable access. It has been shown that the rate of no-shows and long waiting room times is not the same for all patients, and there are associations between these negative experiences and patient demographics.[14] AI-assisted scheduling can make access to

pediatric (neuro)radiology more equitable, regardless of the socioeconomic status of patients.[15]

- Prioritization of reporting: Once images are acquired, AI algorithms can check for various urgent imaging findings which necessitate urgent or emergent reporting, such as hemorrhage, hydrocephalus, or impending herniation. If such an urgent or emergent imaging finding is present, the examinations can be flagged and the reporting pediatric neuroradiologist can be automatically alerted. In the future, AI algorithms may also be trained to flag the need for subspecialty reporting, in addition to indicating the degree of urgency.
- Communication of urgent, emergent, or unexpected findings: When urgent, emergent, or unexpected findings are found on pediatric neuroimaging, they need to be communicated to the referring provider. AI algorithms using natural language processing can screen radiological reports for indicators of urgent, emergent, or unexpected findings and either alert the reporting pediatric neuroradiologist to the necessity to communicate these or even prepare the communication, similarly to a reading room assistant.

Abnormality Detection

AI-based abnormality detection in pediatric neuroradiology is inherently different from adult neuroradiology as it will need to take the age and physiologic developmental stage of the child into account. Normal brain imaging in a neonate differs vastly from normal brain imaging in an adolescent, which makes the AI-based detection of a deviation from a typical developmental pattern more challenging. AI-based detection algorithms in pediatric neuroradiology will therefore need to rely on typical developmental trajectories for various imaging features and parameters. These may, among others, include myelination patterns and myelin volumes, global or focal brain parenchymal volumes, cortical thickness, CSF volumes, and sulcation patterns. One must also factor in brain development in premature neonates, which can be delayed for years after birth compared with term neonates.

In addition, AI-based abnormality detection can play an important role in identifying (and subsequently flagging) urgent and emergent imaging findings that require immediate attention, such as hemorrhage, acute ischemia, mass effect, or impending herniation. These detection algorithms can be more similar to AI algorithms in adult neuroradiology, but they nevertheless require consideration of the age and development of the child, which makes them more complex. A relatively large set of normal cases is usually required to train an abnormality-detection AI model, which learns the distribution of normal images. The deviation of a given image from the learned distribution of normal cases determines whether there is an abnormality in the image. This represents a semi-supervised AI algorithm where only normal cases are needed for training. Generative adversarial networks, and diffusion models have recently been used for abnormality detection for different disease, including brain tumors in adults.[16,17]

AI-based anomaly detection algorithms can also be helpful in pattern recognition of previously unrecognized disorders. When a similar imaging pattern is detected in a large data base, clinical and genetic similarities can then be investigated.

Classification

AI-based classification tasks already play a role in pediatric neuroradiology, and this is expected to grow in importance in the years to come. The classification of neuropediatric disorders has become markedly more complex in the last decade. One example for this is the classification of pediatric brain tumors, with the recent 5th edition of the WHO classification of CNS tumors being reflective of these molecular-driven changes.[18,19] What used to be one tumor category (eg, "medulloblastoma"), is now divided into groups and subgroups based on molecular markers. AI algorithms must reflect this increasing complexity. They are expected to evolve along with the evolution of the molecular-based tumor classification, and AI researchers need to be well versed in these evolving classifications to remain clinically relevant. Molecular-based tumor classification can lead to individualized treatment planning, significantly improving patient outcome. Currently, the molecular landscape of brain tumors is more complex and heterogeneous in the pediatric age range compared with adults. At the same time, these tumors are less common and sample sizes are typically smaller, which is a challenge for AI algorithm development. AI-based classification algorithms are usually trained in a fully supervised manner where large enough sample sizes are needed for each of the classes (eg, tumor types). To overcome the small sample sizes in pediatric neuroradiology, transfer learning may be considered. However, it has been shown that differences in MR imaging signal characteristics between pediatric and adult brain tumors pose a challenge for using transfer learning methods.[20] Therefore, more advanced generative adversarial network and transformer-based data augmentation methods may be needed to tackle this problem.[21,22]

AI-based classification tasks are also important for other parts of pediatric neuroradiology, beyond tumor imaging. Examples include neuroinflammatory disorders, such as multiple sclerosis, neuromyelitis optica spectrum disorder, anti-MOG associated disease and autoimmune encephalitis, and metabolic disorders such as leukodystrophies. The classification of these disorders has also become more complex in the last decade, and AI algorithms will likely play an increasing role in their imaging-based classification.[23-26]

Prognostication

Deriving a prognosis based on imaging features is important for counseling and therapeutic decision making. AI-based algorithms can be trained to estimate molecular information, which in turn contains prognostic information.[27] On the other hand, AI can also directly predict prognostic information (eg, on overall survival, progression-free survival, or neurodevelopmental outcome), depending on the data with which the algorithms were trained.[28] Imaging-based prognostication with AI algorithms will likely become more important in pediatric neuroradiology in the next decade, especially in neuro-oncological imaging and neonatal imaging. The ability to predict prognosis of a neonate can help deliver earlier and more accurate treatment options, which can improve outcomes.

Treatment–Response Prediction

Treatment–response prediction at the earliest possible time point is of utmost importance for precision child health, and ultimately for health outcomes. The earlier we know whether a neuropediatric disorder (eg, a brain tumor, a neuroinflammatory disease, or an epileptogenic lesion) responds to a given therapy or not, the earlier the treatment can be adapted. Ideally, treatment response could be predicted on pretherapeutic imaging, and the most effective therapy can be chosen beforehand.[29] Alternatively, AI-based response prediction can be performed on post treatment imaging. For the best efficacy, it will be important to know the optimal time window between initiation of therapy and treatment–response prediction, which will be different for different tumor types or disease entities — and possibly also will be different for different age groups. Follow-up imaging schedules as well as therapeutic regimens could then be individualized leading to a more precise and personalized treatment scheme, which will eventually help in containing healthcare costs.

Image-to-Image Translation

AI-based image-to-image translation algorithms have recently been shown to enable the creation of images of a different contrast or technique based on acquired images. These algorithms are trained on imaging examinations where both types of acquisitions or modalities were present. Examples are the generation of PET images from MR imaging examinations or of perfusion-weighted images from standard MR imaging sequences; both studies were in adults.[30,31] These image-to-image translation techniques have been mostly studied in adult neuroradiology, but it is likely that they will play a bigger role in pediatric neuroradiology in the years to come. AI-based augmentation of data sets is another potential application for image-to-image translation. Given that pediatric neuroimaging generally lacks large data sets, and considering the prevalence of rare diseases or rare molecular subtypes, image-to-image-translation can be used to artificially increase the size of training sets for classification models.

Rare Diseases

AI applications for rare diseases are a challenge in pediatric neuroradiology as case numbers are low and often not sufficient for training, validating, and testing complex AI algorithms. Transfer learning and artificial augmentation of data sets may be helpful in this setting. In addition, AI algorithms can be helpful in identifying rare diseases among more common disorders and flag these for subspecialty consultation. An example would be the identification of a rare tumor type among more common tumors, for example, an embryonal tumor with multilayered rosettes among other pediatric embryonal brain tumors. Our understanding of the pathophysiology, imaging findings, and response patterns of these rare disorders are usually still quite limited, which is a challenge for developing AI algorithms.

In rare diseases that have yet to be discovered, imaging patterns may be flagged by AI algorithms that point pediatric neuroradiologists to new disease entities, such as a metabolic disorder or leukodystrophy. This pattern-based approach can be based on institutional or multicentric databases or registries or may rely on publicly available imaging databases.[32,33] This may not only allow the detection of new disease entities, but may also spark development of new therapeutic approaches.

AI Reliability in Pediatric Neuroradiology

To date, there is a large translational gap between the development of AI algorithms and actual clinical reality in radiology in general, but specifically in pediatric neuroradiology. One of the most important reasons for this disconnect is the elusive "black-box" nature of AI algorithms.[34] This translates into the absence of explainability in AI algorithms, which may lead to the lack of trust by pediatric neuroradiologists in AI algorithms. A human-centered AI workflow is required where 1) the results of AI algorithms are accurate, repeatable, and generalizable; 2) the AI results are adequately explainable and understandable by radiologists; 3) the radiologists can make a change to the AI algorithm (eg, changing the weight of loss function depending on the importance of input) or the input data (eg, changing the ROI), retrain the model, and monitor the results; and finally, 4) the radiologist's feedback is taken into consideration by the AI algorithm to ensure perpetual improvement of the algorithm.

Integrating AI into a PACS

Currently, PACS systems do not provide a plugin mechanism for AI algorithms; thus, AI vendors must develop special interfaces for communication with PACS. This leads to stand-alone AI algorithms, which are not properly integrated with PACS systems, making their usability a challenge. Integration of AI algorithms into clinical practice requires a seamless integration into the hospital's PACS systems, which requires a more AI-friendly interface for PACS systems.

CONCLUSIONS

AI will play an important role in pediatric neuroradiology in the next decade. Its impact will be different from adult neuroradiology, due to the high degree of subspecialization, lower number of pediatric neuroradiologists, wide spectrum of neuropediatric disorders with often relatively low case numbers, and age-dependent variation in imaging patterns. While AI algorithms will play an important role, humans will not only need to be in the loop, but in the center of pediatric neuroimaging.

Disclosure forms provided by the authors are available with the full text and PDF of this article at www.ajnr.org.

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