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Review Article

Artificial Intelligence in Neuroendovascular Procedures

Kenichi Kono

Recent advances in artificial intelligence (AI) have significantly transformed neuroendovascular procedures, offering innovative solutions for image analysis, procedural assistance, and clinical decision-making. This review examines the current state and future potential of AI applications in neuroendovascular interventions, focusing on 3 topics: AI-based image recognition, real-time procedural assistance, and future developments. From a research perspective, deep learning algorithms have demonstrated reasonable accuracy in vascular structure analysis and device detection, successfully identifying critical conditions such as vascular perforation, aneurysm location, and vessel occlusions. Real-time AI assistance systems may have potential clinical utility in various procedures, including carotid artery stenting, aneurysm coiling, and liquid embolization, potentially enhancing procedural safety and operator awareness. The future of AI in neuroendovascular procedures shows promise in integration with robotic systems and applications in medical education. While current systems have some limitations, ongoing technological advances suggest an expanding role of AI in enhancing procedural safety, standardization, and patient outcomes.

Keywords artificial intelligence, real-time assistance, neuroendovascular procedures, deep learning, image recognition

Introduction

In recent decades, neuroendovascular procedures have undergone remarkable advancements driven by technological innovations in imaging, devices, and artificial intelligence (AI). The integration of AI into neuroendovascular treatment shows promise for transforming approaches to cerebrovascular disorders, with emerging opportunities to enhance diagnostic accuracy, improve patient selection, and optimize procedural outcomes.[1,2] Although this technological evolution is in its infancy, it represents an important step toward the development of more precise and efficient treatment strategies.

Neuroendovascular procedures, which require precise navigation through intricate vascular networks and real-time decision-making, are particularly suitable for AI assistance. Recent advances in deep learning, particularly in image processing and real-time analysis, have demonstrated promising results in various applications, including automatic vessel segmentation, device tracking, and predictive modeling of patient outcomes.[3–5]

This review examines the evolution, current state, and future potential of AI in neuroendovascular procedures, focusing on the progression of interventional imaging analysis, real-time assistance systems during procedures, and future developments in the field.

AI-Based Image Recognition

Recent advances in AI have significantly enhanced the image recognition capabilities in neuroendovascular procedures, primarily concerning device recognition and vascular structure analysis[1,2]. These technological developments have the potential to improve both procedural accuracy and patient outcomes.

iMed Technologies, Tokyo, Japan

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Corresponding author: Kenichi Kono. iMed Technologies, 202, 4-1-13, Yushima, Bunkyo-ku, Tokyo, 113-0034, Japan
Email: vyr01450@gmail.com

Vascular recognition

Deep learning has been increasingly applied in neurointerventional imaging to enhance diagnostic accuracy and assist clinicians. Specifically, it has been used to detect critical conditions such as vascular perforation automatically,[6] accurately identify aneurysm locations,[7] detect occlusions,[8] and classify thrombolysis in cerebral infarction (TICI) scores.[9]

Su et al.[6] used a spatiotemporal deep learning approach to automatically detect and localize intracranial vessel perforations using digital subtraction angiography (DSA) during endovascular thrombectomy. Evaluated using multicenter datasets (MR CLEAN Registry, MR CLEAN-NoIV Trial, HERMES), the model achieved an area under the curve (AUC) of 0.93 for perforation detection at the series level, with localization precision and recall scores of 0.83 and 0.70, respectively. Jin et al.[7] developed an automated deep-learning model for the detection and segmentation of intracranial aneurysms using 2D DSA sequences. Trained on over 2200 DSA sequences, the model achieved a patient-level sensitivity of 97.7% and accurately detected 89.3% of the aneurysms in a test set, demonstrating reliable accuracy in localizing aneurysms. Mittmann et al.[8] demonstrated a deep learning method to classify DSA image sequences from thrombectomy procedures for acute ischemic stroke into “thrombus-free” and “non-thrombus-free” categories. Using data from 260 patients, the model achieved an AUC of 0.94, indicating high accuracy in identifying the presence of a thrombus. This approach aims to prevent thrombus oversight during thrombectomy and to enhance treatment safety and effectiveness. Su et al.[9] developed autoTICI, which is an automated method that uses a multiphase convolutional neural network to classify DSA images into distinct vascular phases, followed by pixel-based reperfusion quantification. Tested on a multicenter dataset, autoTICI achieved an AUC of 0.81.

These studies demonstrated that AI-based imaging analysis in neuroendovascular procedures has achieved clinically acceptable accuracy levels for critical applications. These advances in automated detection and classification systems represent practical tools that can enhance procedural safety and standardize clinical assessments in neurointerventional practice.

Device recognition

AI systems have evolved to provide precise detection and tracking of various endovascular tools. Deep learning models can automatically identify and track catheter tips, guide wires, and stent devices during procedures with increasing accuracy.[10–13]

For example, Ghosh et al.[10] developed an automated approach for segmenting catheters and detecting their tips in cerebral angiography using advanced deep learning models, specifically “no-new-Net” (nnUNet) and “Topology-Aware Geometric Deep Learning” (TAG-DL). The nnUNet model achieved the highest accuracy, with a centerline dice score of 0.98 and a tip-distance error of 0.43 mm. Chen et al.[13] presented a 2-phase deep learning method for real-time guidewire shape extraction from fluoroscopic images, which is crucial for cerebral and cardiovascular interventions. Phase 1 identifies the image regions with guidewire structures, and Phase 2 accurately segments these regions. The approach achieved 99% accuracy with negligible false positives, processing each image in 78 ms. This method enhances accuracy and efficiency and meets real-time clinical application demands.

Real-Time AI Assistance

Neuroendovascular procedures require operators to monitor multiple devices across multiple screens simultaneously, creating a significant cognitive burden and increasing the potential risk of overlooking critical device movements. Recent clinical studies have demonstrated the successful implementation of real-time AI assistance to address these challenges through automated device tracking and operator notification systems using the AI software Neuro-Vascular Assist (iMed Technologies, Tokyo, Japan),[14–16] and has been approved for medical use in Japan. This system has been installed in several institutions and is used for daily neurointerventional procedures in Japan.

The software analyzes both subtracted and unsubtracted images in real-time, with the processed outputs displayed on the monitors in the angiography suite. The system includes a sterilized mouse interface that allows operator control during the procedures, with a setup time of 1 min. The system provides comprehensive device detection and tracking capabilities, including the automatic recognition of catheter tips (displayed as rectangles), guidewire tips (displayed as triangles), and coil markers (displayed as circles) (**Fig. 1** and **2**). For liquid embolic procedures, the system provides color overlay visualization of the embolic material. These detected devices are monitored in real-time, with the system providing both audio and visual notifications through color changes on the display when significant movements or positions are detected. Operators can define custom regions of interest (ROI) for specific

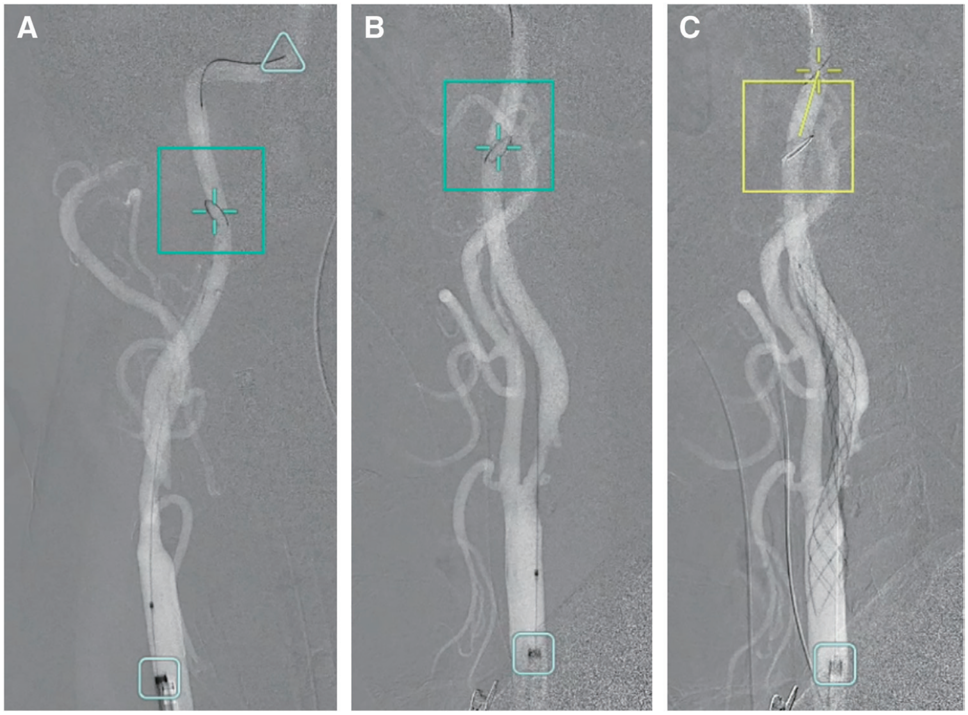

Fig. 1 Real-time AI-assisted carotid artery stenting. (**A**, **B**) The AI system tracks multiple devices in real-time. The guiding catheter is tracked and marked as a rectangle in the frontal image (**A**) and the lateral image (**B**). The wire tip is marked as a triangle, and the filter is marked as a crosshair. The ROI is a green square. (**C**) When the filter moves out of the ROI, the AI system notifies the operator with a sound and changes in color from green to yellow. AI, artificial intelligence; ROI, region of interest

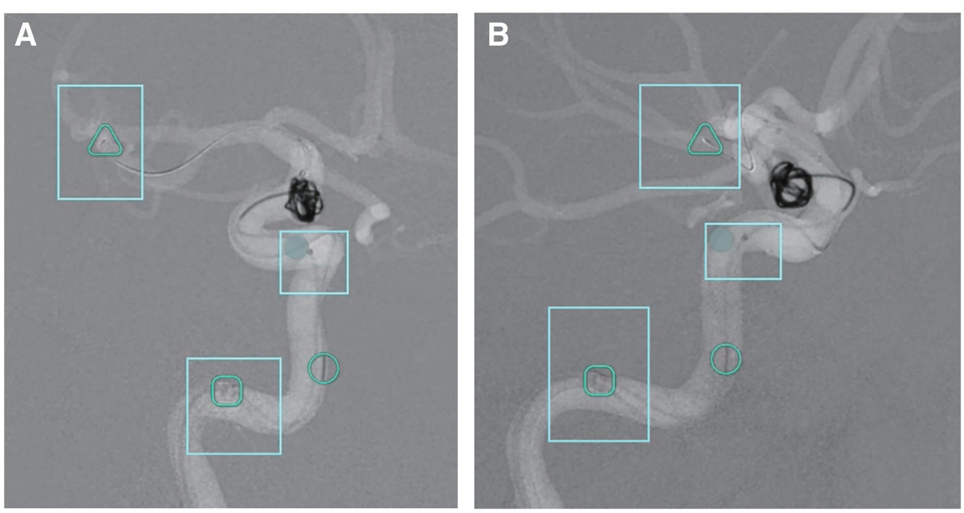

Fig. 2 Real-time AI-assisted coil embolization for a cerebral aneurysm (**A**, **B**) The AI system tracking multiple devices in real-time. The distal access guiding catheter is tracked and marked as a rectangle in the frontal image (**A**) and the lateral image (**B**). The wire tip of the balloon is marked as a triangle, and the coil marker is marked as a circle. The ROIs are indicated by green squares. AI, artificial intelligence; ROIs, region of interests

monitoring, and the system notifies the user when the device moves out of the ROI.

Multiple clinical validation studies demonstrated the accuracy and utility of the system for carotid artery stenting,[14] coil embolization for cerebral aneurysms,[15] and liquid embolization.[16] For carotid artery stenting procedures (n = 6), the system demonstrated 82% precision and 94% recall, generating notifications in 23% of instances, which resulted in filter adjustment (**Fig. 1**). For aneurysm coiling procedures (n = 9), the system achieved precision and recall rates of 92.7% and 97.2%, respectively (**Fig. 2**). Notably, 19% of the guidewire notifications led to device

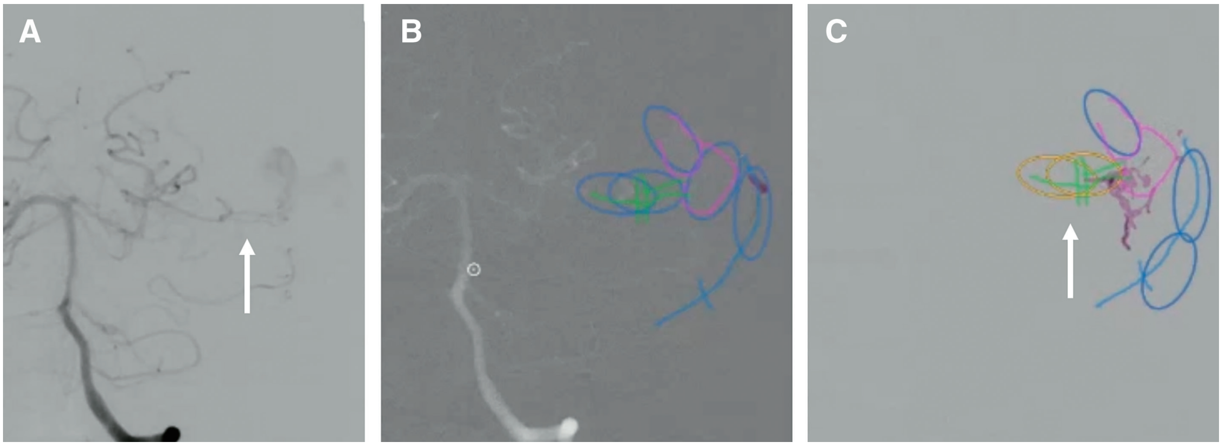

Fig. 3 Real-time AI-assisted Onyx embolization for a tentorial dural arteriovenous fistula. (**A**) The SCAs observed near the fistula (arrow). (**B**) The SCAs are outlined with green lines. Two elliptic boundaries are set around the SCA feeders to enable staged notification of Onyx migration. (**C**) Onyx is injected from the middle meningeal artery; upon penetration into the SCA feeder, the operator is notified via an audible sound and a color change to yellow (arrow), prompting a pause in injection. AI, artificial intelligence; Onyx, Medtronic, Dublin, Ireland; SCAs, superior cerebellar arteries

repositioning. In the liquid embolization procedures (n = 8), the system showed 100% precision and 92.0% recall, with 28.3% of the notifications prompting injection pauses, suggesting potential clinical usefulness in preventing unintended vessel embolization (**Fig. 3**).

Technical performance analysis reveals minimal impact on workflow, with an image processing delay of approximately 0.33 seconds compared to live fluoroscopy, which has not been reported to cause any clinical issues.[15] The ability of the system to analyze both subtracted and unsubtracted images allows seamless integration with the preferred visualization modes of the operator.

Current limitations include the requirement for manual ROI setting, occasional false notifications due to image quality issues, and the potential for misrecognition under complex anatomical situations. Additional procedural time is needed for ROI setup, with approximately 10 seconds for each ROI. However, these limitations are generally considered acceptable, given the demonstrated potential benefits of the system in enhancing procedural safety and operator awareness.

Future Perspective

The next generation of AI-assistance systems is expected to offer improved accuracy and expanded functionality. The development of more sophisticated deep learning algorithms could enable the real-time analysis of complex anatomical structures and predict potential complications. The integration of pre-procedural imaging and advanced visualization techniques could provide more comprehensive procedural guidance. Additionally, improvements in the user interface and customization options can further reduce the cognitive load on operators.

Combination with robotic systems

The convergence of AI assistance and robotic systems is a promising direction for neuroendovascular procedures. Robot-assisted endovascular treatment of cerebral aneurysms has already demonstrated safety and effectiveness.[17] Chi et al.[18] demonstrated a learning-based robotic catheterization platform that uses non-rigid registration to adapt to patient-specific vascular anatomy. The system achieved high cannulation success rates (98.1% in dry simulation and 94.4% in continuous flow) and reduced contact forces by 33.3% compared with manual catheterization. This approach demonstrates the potential for safer and more precise catheter navigation during complex endovascular procedures. Ploscaru et al.[19] proposed an AI- and cloud-based platform for fully automated percutaneous coronary intervention (PCI) guidance using coronary angiography images. The system uses AI algorithms to reconstruct the 3D coronary anatomy and perform functional assessments, including pre- and post-PCI fractional flow reserve calculations.

These studies show that the combination of real-time AI monitoring with robotic precision can enhance procedural safety and standardization. AI systems can provide automated safety boundaries and motion constraints for robotic systems, while real-time tracking enables more precise robotic navigation. This synergy between AI and robotics could lead to semiautonomous procedures with enhanced safety features and reduced operator burden.

Educational effect

Real-time AI systems offer significant potential for the training and assessment of neuroendovascular procedures. These systems can provide objective metrics for procedural performance, enabling a standardized evaluation of the technical skills of the operator. Visualization and notification features could serve as valuable teaching tools to help trainees understand critical decision points during procedures. The recording and analysis of AI-monitored procedures could facilitate the development of best practice guidelines and improve our understanding of the technical aspects of various procedures.

Rolls et al.[20] used video motion analysis to demonstrate that anatomical complexity increases tool movement during carotid artery stenting (CAS). In their simulations, increased anatomical complexity reduces the efficiency of the guidewire and catheter manipulation in CAS. Mazomenos et al.[21] evaluated catheter manipulation skills of surgeons during transcatheter aortic valve implantation using objective metrics. Twelve surgeons (6 experts and 6 novices) performed the tasks using traditional and robotic catheters. Their findings show the experts had shorter procedure times and smoother motion.

AI systems are poised to transform neuroendovascular training using objective performance metrics and standardized evaluation methods. Initial studies showing the ability of AI to analyze procedural complexity and distinguish expert performance suggest that these systems will become invaluable for developing surgical skills and establishing evidence-based training protocols for future physicians.

The advancement of AI in neuroendovascular procedures promises enhanced accuracy through sophisticated deep learning algorithms, whereas its integration with robotic systems demonstrates the potential for improved procedural safety and precision. These technological synergies, combined with the emerging role of AI in medical education, are set to revolutionize both the practice and training of future endovascular interventions.

Social and ethical considerations of the AI system

While AI technologies show great promise in neuroendovascular procedures, their implementation raises several important social and ethical considerations. The high initial costs of AI systems, including that for hardware, software licenses, and maintenance, may create disparities across healthcare facilities in access to these advanced technologies.[22,23] Additionally, regular AI system updates would increase the total cost burden of institutions.

Additionally, privacy and data security concerns are valid, particularly regarding the collection and storage of patients' imaging data used for AI training and analysis.[23,24] There are also questions about medical liability and responsibility when AI systems are involved in clinical decision-making. While AI systems serve as assistant tools, the determination of accountability in cases where AI recommendations contribute to adverse outcomes requires careful consideration.

Conclusion

Recent advances in AI have transformed neuroendovascular procedures from automated image analysis to real-time procedural assistance. Current AI systems demonstrate remarkable capabilities in device tracking, vessel recognition, and operator support, showing particular promise for enhancing procedural safety and efficiency. The implementation of real-time AI assistance is a significant step forward in providing operators with automated monitoring and timely notifications during complex interventional procedures. Although current systems have certain limitations, ongoing technological developments, including integration with robotic systems and training applications, suggest an expanding role of AI in advancing neuroendovascular medicine. As these technologies continue to evolve, they are expected to become integral components of procedural workflows, contributing to improved safety, standardization, and, ultimately, better patient outcomes.

Disclosure Statement

KK is a CEO and holds shares in iMed Technologies.

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