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Research Article

Neurointerventional Radiology: History, Present and Future

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Abstract

Neurointerventional Radiology (NIR), encompassing neuroendovascular surgery, endovascular neurosurgery, and interventional neurology, is an innovative and rapidly evolving multidisciplinary specialty focused on minimally invasive therapies for a wide range of neurological disorders. This review provides a comprehensive overview of NIR, discussing the three routes into the field, highlighting their distinct training paradigms, and emphasizing the importance of unified approaches through organizations like the Society of Neurointerventional Surgery (SNIS).

The paper explores the benefits of co-managed care and its potential to improve patient outcomes, as well as the role of interdisciplinary collaboration and cross-disciplinary integration in advancing the field. We discuss the various contributions of neurosurgery, radiology, and neurology to cerebrovascular surgery, aiming to inform and educate those interested in pursuing a career in neurointervention. Additionally, the review examines the adoption of innovative technologies such as robotic-assisted techniques and artificial intelligence in NIR, and their implications for patient care and the future of the specialty.

By presenting a comprehensive analysis of the field of neurointervention, we hope to inspire those considering a career in this exciting and rapidly advancing specialty, and underscore the importance of interdisciplinary collaboration in shaping its future.

Introduction

Neurointerventional Radiology (NIR), also known as neuroendovascular surgery, endovascular neurosurgery, or interventional neurology, is an innovative and rapidly evolving specialty that combines the expertise of multiple disciplines to provide minimally invasive therapies for a wide range of neurological disorders.

History of neurointerventional radiology

The origins of NIR date back to the 1960s and 1970s, with the development of selective angiography and the introduction of endovascular therapies for the treatment of neurological disorders. Since then, the field has experienced significant advancements in imaging technology, materials, and procedural techniques, leading to an expansion in its scope and capabilities. Today, NIR encompasses a variety of interventions, such as endovascular treatment of cerebral aneurysms, arteriovenous malformations, stroke management, and carotid artery stenting.

The field's early days can be traced back to the pioneering work of Portuguese neurologist Egas Moniz, who, with Pedro Almeida Lima, developed the first cerebral angiogram in 1920. This technique revolutionized the visualization of cerebral tumor vascular supply and was widely used until being replaced by the advent of Computed Tomography (CT) scans [1,2].

The first minimally invasive endovascular treatment of an intracranial aneurysm was performed in 1939. Gerard Debrun, regarded as the father of interventional neuroradiology, developed a detachable latex balloon catheter to treat carotid cavernous fistulae and giant intracavernous aneurysms [3,4]. This technique was quickly adopted for its novelty and efficiency. In 1990, neurosurgeon Guido Guglielmi introduced a new method to treat intracranial aneurysms using detachable coils [4,5]. The International Subarachnoid Aneurysm Trial in 2005 compared endovascular versus open surgical treatments, demonstrating better independent survival odds and lower morbidity and mortality with endovascular coiling. These findings persisted in the 5-year follow-up, making endovascular coiling a preferred treatment method for ruptured intracranial aneurysms [6].

The Prolyse in Acute Cerebral Thromboembolism (PROACT II) trial revealed increased rates of recanalization and functional independence in patients receiving intra-arterial thrombolysis for acute middle cerebral artery occlusion [7]. Additionally, the MR CLEAN study demonstrated the efficacy and safety of intra-arterial thrombolysis for acute ischemic strokes caused by proximal occlusion in the anterior circulation. IAT led to a 10% absolute reduction in poor outcomes after stroke [8].

Further trials, such as DAWN, DEFUSE 3, and MR RESCUE, highlighted the advantages of mechanical thrombectomy for ischemic strokes, leading to the incorporation of this technique into standard treatment and the relaxation of eligibility criteria. These studies showcased the therapeutic benefits of NIR techniques, offering patients improved chances of recovery and functional independence [9-11]. As advances continue, trials assessing the efficacy and safety of endovascular treatments for ischemic strokes have shown that patients significantly benefit from the integration of neuroendovascular approaches, with some studies even extending the critical window for intervention up to 24 hours [12,13].

Neurointerventional radiology today

Today, NIR is at the forefront of numerous innovative techniques used for treating central nervous system (CNS) pathologies. The growing demand for comprehensive stroke centers, along with the overall expansion of NIR, has led to an increased need for skilled neurointerventional practitioners.

Among the neurointerventional procedures currently available are diagnostic angiograms, dural venous pressure measurements, inferior petrosal sinus sampling, Wada testing, and various neck and spinal diagnostic procedures, including myelography, cisternography, image-guided lumbar puncture, and vertebral biopsy. Therapeutic procedures feature aneurysm coiling, flow diversion stenting, carotid artery stenting, intracranial and spinal arteriovenous fistula embolization, vein of Galen malformation embolization, balloon-assisted endovascular embolization, middle meningeal artery embolization, epistaxis embolization, tumor embolization (e.g., meningiomas and lingual carcinomas), arterial and venous mechanical thrombectomy, venoplasty, venous stenting, arterial angioplasty, and intra-ophthalmic artery chemotherapy [14-19].

Pathways into neurointervention

In the United states, there are three primary pathways to becoming a neurointerventionalist: neurosurgery, radiology, and neurology as outlined by the SNIS (Figure 1). Each pathway offers unique perspectives, training experiences, and opportunities for professional development [20,21].

Neurosurgery is a surgical specialty centered on the diagnosis and management of CNS disorders, including the brain and spine. The pathway to becoming a neuro-interventionalist through neurosurgery typically involves completing a 7-year neurosurgical residency followed by a 1-2 year fellowship in endovascular neurosurgery or interventional neuroradiology. Enfolded fellowships are often performed within residency, followed by 1 year of training in endovascular neurosurgery. The unique strength of this route is the combination of an extensive surgical background with interventional techniques, providing expertise in managing complex cases requiring both open and endovascular approaches. Furthermore, complications arising during a procedure can be addressed through immediate conversion to open surgery [4,21-25].

Radiology offers a diagnostic perspective, emphasizing medical imaging techniques and image interpretation. To become a neurointerventionalist via the radiology route, one must complete a preliminary internship year, 4-year diagnostic radiology residency and then a neuroradiology fellowship, usually lasting 1-2 years, followed by additional training in interventional neuroradiology. Alternatively, an integrated interventional radiology residency, which typically takes 5 years following the completion of a preliminary internship year, can be completed followed by training in interventional radiology. The unique strength of this pathway lies in the mastery of catheter skills acquired during training and the thorough understanding of diagnostic imaging's applications, which guide the planning and execution of neurointerventional procedures effectively [21,26].

Lastly, neurology focuses on the diagnosis and non-surgical management of neurological disorders. Trainees with a neurology background possess extensive clinical

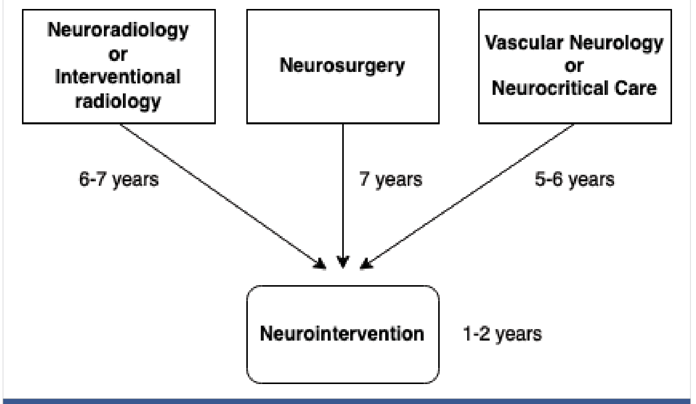

Figure 1: Neurointerventional training pathways based on primary specialty as outlined by the SNIS.

skills and a deep understanding of the natural progression of vascular pathologies. The pathway to NIR through neurology requires a 4-year neurology residency, followed by a 1-2 year vascular neurology/stroke or neurocritical care fellowship, and additional training in interventional neuroradiology. Neurologists bring a thorough understanding of the medical aspects of neurological diseases, which can be invaluable in assessing and managing patients before, during, and after neurointerventional procedures [21,27].

In Figure 2, Cox, et al. demonstrate the approximate distribution of neurointerventionalists by primary specialty using data adapted from [28]. Other specialties may contribute to NIR procedures. For example, orthopedic surgeons contribute significantly to percutaneous spine procedures. Cardiologists and vascular surgeons often perform carotid endarterectomies. The distribution is similar in Canada, with 52% being neuroradiologists, 38% neurosurgeons, and 9% neurologists [29].

Specialty integration

To further enhance collaboration and advance the field of neurointervention, a unified approach that leverages the strengths of organizations, joint conferences, online platforms, and continuing education is crucial. By adopting such a comprehensive strategy, professionals from various backgrounds can share their knowledge, experiences, and ideas, thereby fostering innovation and improving patient care.

Organizations such as the Society of NeuroInterventional Surgery (SNIS) play a pivotal role in bringing together professionals from diverse backgrounds, including neurosurgery, neuroradiology, and neurology [30]. SNIS provides a platform for these specialists to collaborate on research, share best practices, and develop guidelines for patient care. Variability in recommendations among specialties is a concern, as clinicians from different specialties may have different approaches to patient care

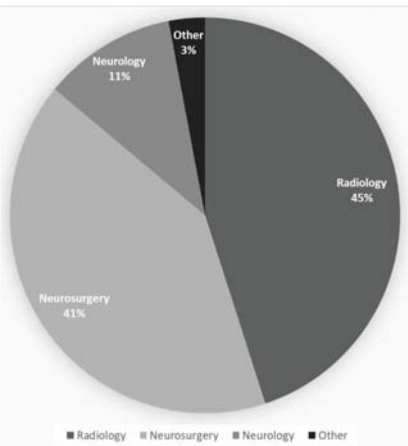

Figure 2: The percentage of each specialty that performed intracranial endovascular procedures in 2016. Data adapted from [28].

[31]. Organizations such as SNIS allow for standardization of guidelines between organizations and specialties. Moreover, by facilitating interaction and cooperation among its members, and providing opportunities for joint training and learning, SNIS ensures that the latest advancements in neurointerventional techniques and therapies are disseminated across the field.

Joint conferences represent another valuable opportunity for collaboration. These events allow attendees to exchange ideas, present research findings, and discuss new developments in the field of neurointervention. By hosting sessions and workshops that cater to various backgrounds and skillsets, joint conferences provide an inclusive environment that encourages the development of interdisciplinary relationships and mentorship.

In addition, online platforms have become increasingly important in promoting communication and collaboration in the field of neurointervention. These platforms include forums, webinars, social media, and virtual conferences, which offer opportunities for professionals to connect and share their expertise. By leveraging these digital resources, specialists can keep up-to-date with the latest advancements in their field, regardless of geographical location.

Continuing education is essential for professionals in the rapidly evolving field of neurointervention. Many organizations, including SNIS, offer continuing education courses, workshops, and certifications [30]. Through regular training and educational programs, neurointerventionalists from all specialties can hone their skills, acquire new techniques, and stay informed about recent research findings and technological advancements.

Another opportunity for knowledge exchange is through common grand rounds, where professionals from different specialties present clinical cases and share their perspectives, fostering cross-disciplinary learning. Multidisciplinary team meetings are another essential avenue for collaboration, as they allow specialists to discuss individual cases and develop comprehensive treatment plans. These meetings facilitate the identification of best practices, encourage consensus-building, and promote coordinated care. Additionally, joint clinical rotations can enhance understanding of the roles and contributions of other specialties in neurointervention, building a strong foundation for interdisciplinary practice.

Engaging professionals from various specialties in collaborative research projects can lead to innovative solutions and advancements in the field of neurointervention. Working together on research initiatives allows specialists to share their expertise and insights, fostering a culture of cooperation and mutual learning. Furthermore, developing interdisciplinary training programs can help bridge the gap between different specialties by providing education on the diverse aspects of neurointervention. These programs should focus on the unique contributions and skillsets of each specialty while emphasizing the importance of collaboration for optimal patient care. By bringing together specialists from various backgrounds, shared clinical facilities can optimize resource utilization, promote the exchange of ideas, and create a more efficient and effective healthcare environment. The integration of specialties in a shared setting may lead to better decision-making, improved patient care, and enhanced outcomes in the field of neurointervention.

Co-managed care

The co-managed care model has gained traction in various healthcare settings worldwide, demonstrating significant benefits for neurosurgical patients, including improved prognosis and recovery from ischemic stroke [32], subarachnoid hemorrhage [33], and head trauma [34]. The diverse perspectives and expertise of healthcare professionals, including neurointerventionalists, neuro-endovascular surgeons, neurointensivists, and other healthcare professionals, have resulted in better resource utilization and the establishment of effective emergency protocols [32].

Auerbach, et al. conducted a retrospective study that highlighted the positive impact of a co-managed care model involving neurosurgeons and hospitalists on neurosurgical patients, resulting in improved care quality, patient satisfaction, and reduced hospital costs [35]. Although the study showed minimal improvement in patient mortality and outcome, it underscores the potential benefits of co-managed care in advancing patient care. Josephson, et al. demonstrated the effectiveness of co-managed care in addressing specific variables such as fever, antibiotic use, and the diagnosis of ventilator-associated pneumonia, which were better managed through this collaborative approach [33]. Co-managed care has also been shown to enhance documentation and healthcare flow in neurosurgical intensive care units [34].

Various co-managed care models have been proposed and implemented to address the rising healthcare costs and potential decline in patient safety [36]. These models emphasize collaboration among healthcare professionals, such as neurointerventionalists, surgeons, and anesthesiologists, to provide comprehensive care for patients [36]. Interdisciplinary approaches, on the other hand, involve physicians from similar backgrounds working together to manage patient care [36]. Executive management teams typically oversee the recruitment of diverse medical and surgical representatives who bring unique value to clinical cases [37]. Improvements in care are often measured using quality metrics tailored to individual hospitals, including enhanced physician-to-physician communication and patient handoffs. Many hospitals have shifted from a centralized administration to allowing physicians greater autonomy in their workflow [37]. Current research advocates for flexibility within co-managed care models, encouraging hospitals to adapt these models to best meet the needs of their patients.

Furthermore, Comprehensive neurovascular centers provide optimal environments for patient treatment, as they offer access to various subspecialty care services. In addition to NIR, these centers ideally include neuroanesthesia, neuro-ICU care, and neurorehabilitation facilities, ensuring comprehensive care for patients with complex needs or complications following a procedure [38].

Occupational exposure

Occupational hazards such as exposure to ionizing radiation and wearing lead during procedures pose significant health risks to neurointerventional radiologists, including an increased risk of cancer and back pain [39]. These risks may limit the number of women in the field due to fear of radiation exposure, particularly during pregnancy [40]. To recruit more talented physicians and further expand the horizons of neurointervention, it is essential to explore solutions that minimize radiation exposure and overcome ergonomic obstacles.

Future of NIR

The development and implementation of robotic-assisted techniques offer significant potential for improving patient care, minimizing radiation exposure, and improving ergonomics in neurointervention. These innovations have shown promise in treating patients with severe symptomatic carotid stenosis and aneurysms of the basilar artery. In a recent Canadian study, a patient with a basilar trunk aneurysm underwent a stent-assisted coiling procedure with nearly all steps robotically performed, except for the manual placement of the guide-sheath and coaxial catheter [41]. The robot's ease of use and smooth, precise movements facilitated navigation, stent placement, and coiling, demonstrating the potential for even greater robotic involvement in the future.

Using robotic-assisted techniques can reduce radiation exposure and ergonomic challenges faced by neurointerventional radiologists, leading to a more diverse and inclusive field that attracts a broader range of talented physicians. Furthermore, advancements in technology, such as sophisticated simulators and artificial intelligence (AI), will likely continue to enhance patient outcomes and reduce training differences among interventional practitioners. AI algorithms may help radiologists detect life-threatening neurological conditions more rapidly, such as ruptured aneurysms, aneurysm growth, and ischemic strokes [42-45]. Faster detection may lead to quicker neurovascular team notifications and improved patient outcomes.

As clinical trials continue to investigate the efficacy of robotic-assisted endovascular procedures, the adoption of this modality among practitioners has the potential to increase care coverage across the nation. Remote care delivery through robotic systems can provide access to specialty care in underserved areas [46-48]. However, healthcare facilities must address potential challenges, such as converting a robotic case to a manual case in case of complications or connectivity issues, before investing in this technology.

The implementation of robotic devices will require updates to the medical-legal framework and consideration of federal logistics and regulations regarding licenses, hours of coverage, and liability. As remote care becomes more widespread, it is essential to ensure that specialists are available to take over patient care in case of complications.

In summary, embracing robotic-assisted techniques and technology in neurointervention holds promise for improving patient care, attracting a more diverse pool of trainees, and expanding care coverage to underserved areas. By overcoming the challenges associated with implementing these advancements, the field of neurointervention can continue to grow and innovate.

Conclusion

In conclusion, the field of interventional neuroradiology, neuroendovascular surgery, and interventional neurology holds immense promise for continued growth and advancement in the coming years. Not only does it offer the potential for remote care coverage in emergency situations, but it also demonstrates the capacity to expand into a wide range of elective procedures and oncological cases, allowing patients to receive interdisciplinary care closer to their homes.

To ensure a consistent pipeline of talented trainees entering the field of neurointervention, it is important to raise awareness and foster engagement at the medical school and residency levels. By emphasizing the exciting opportunities and innovative potential of a career in radiology, neurology, or neurosurgery leading to neurointervention, medical students can make more informed decisions about their specialty choices and contribute to the ongoing evolution of this critical field.

As the field continues to develop and embrace new technologies, such as robotic-assisted techniques and artificial intelligence, it will be better positioned to address complex patient needs and provide comprehensive care in both emergency and non-emergency situations. By nurturing interdisciplinary collaboration and promoting the specialty to the next generation of physicians, the field of neurointervention will undoubtedly continue to flourish and make a significant impact on patient care and outcomes.

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