BMC Surgery

REVIEW

Open Access

Microvascular decompression: a contemporary update

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Abstract

Background Microvascular decompression (MVD) is the gold-standard surgical treatment for cranial nerve compression disorders, including trigeminal neuralgia (TN), hemifacial spasm (HFS), and glossopharyngeal neuralgia (GPN). This review synthesizes historical milestones, recent advances, and evolving techniques in MVD, with a primary focus on these conditions.

Methods A comprehensive literature review was conducted using databases such as PubMed, SpringerLink, Google Scholar, BioMed Central, Scopus, and ScienceDirect. Studies published between 1970 and 2024 were analyzed, emphasizing surgical techniques, clinical outcomes, and technological innovations in MVD. Articles addressing TN, HFS, GPN, and other cranial nerve disorders treated with MVD were selected for detailed evaluation.

Results MVD demonstrates high efficacy, with 80–90% of patients achieving immediate symptom relief. Nevertheless, 15–25% of patients experience symptom recurrence, though long-term outcomes remain favorable. Fully endoscopic MVD has shown potential for enhanced intraoperative visualization, particularly in complex anatomical regions; however, its impact on surgical precision and clinical outcomes is still under investigation. Moreover, innovations in visualization technologies, including three-dimensional exoscopic systems and artificial intelligence-assisted surgery, continue to improve procedural safety and outcomes. Despite these advancements, complications such as hearing loss (1–2%) and cerebrospinal fluid leakage (2–4%) persist, highlighting the need for continuous refinement of techniques.

Conclusions MVD is evolving with the integration of cutting-edge technologies, resulting in improved clinical outcomes and reduced complication rates. Emerging innovations such as robotic-assisted MVD and gene therapies for cranial nerve disorders, including TN and GPN, promise even greater efficacy and precision. However, further research is necessary to standardize surgical protocols and address disparities in healthcare systems globally.

Keywords Microvascular decompression, Trigeminal neuralgia, Hemifacial spasm, Glossopharyngeal neuralgia, Contemporary update

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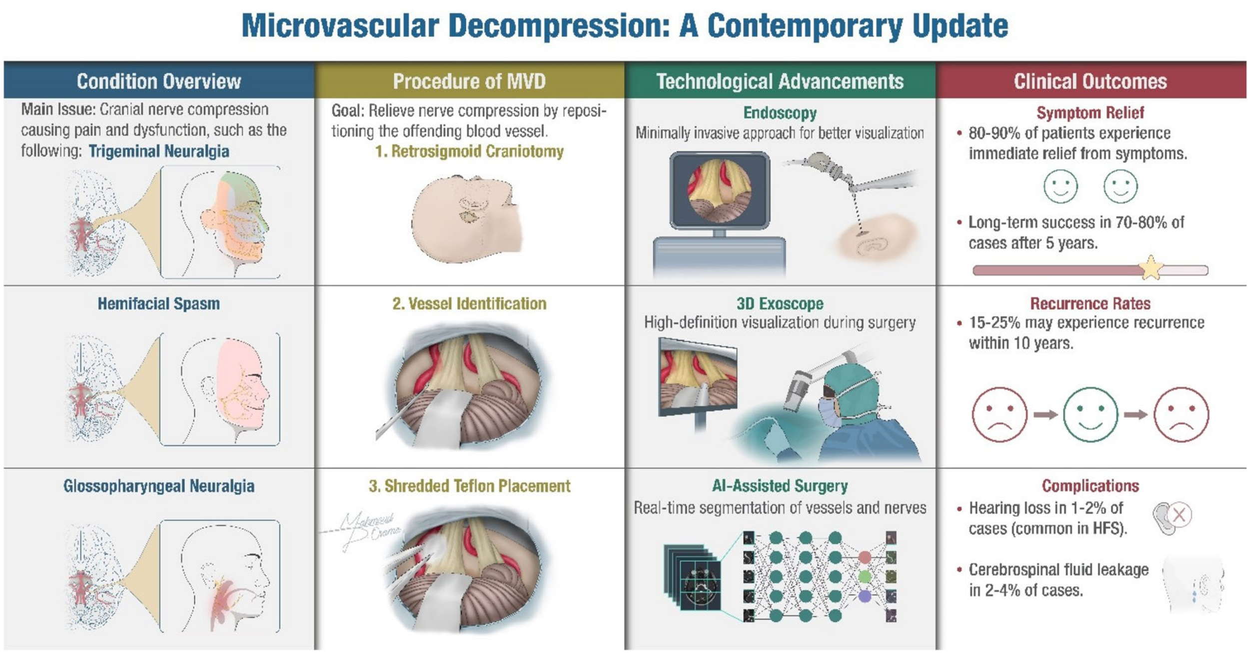
Graphical Abstract



Introduction

Trigeminal neuralgia (TN), often referred to as tic douloureux, is a debilitating condition characterized by recurrent episodes of intense, electric shock-like facial pain. The condition is typically triggered by minor stimuli, such as chewing or light touch, and most commonly affects the mandibular or maxillary branches of the trigeminal nerve. The natural history of TN, as described by Burchiel and Slavin [1], reveals a progressive course where pain episodes become increasingly severe and resistant to medical management over time. Furthermore, as highlighted by Simms and Honey [2], autonomic symptoms such as lacrimation and nasal congestion frequently accompany TN, underscoring the complexity of its pathophysiology. Microvascular decompression (MVD), a cornerstone surgical technique for treating cranial nerve disorders such as trigeminal neuralgia (TN) and hemifacial spasm (HFS), provides significant symptom relief by addressing neurovascular compression at the nerve root entry zone, with Burchiel [3] emphasizing the importance of precise surgical techniques for optimizing patient outcomes (Fig. 1). Walter Dandy made foundational contributions to neurosurgery by pioneering early cranial nerve surgery techniques; however, his methods did not address neurovascular compression as observed in modern MVD procedures [4]. Dr. Peter Jannetta pioneered advancements in the field during the 1960s by elucidating the association between neurovascular compression and cranial nerve dysfunction, leading to the development of the contemporary MVD technique [5]. His innovative use of Teflon implants to separate compressive blood vessels from cranial nerves cemented MVD as the gold-standard surgical treatment for conditions like TN and HFS [6–8]. Subsequently, advancements such as endoscopic-assisted techniques and neuronavigation systems further enhanced the safety, precision, and outcomes of the procedure [9–11].

The emergence of fully endoscopic MVD introduced a minimally invasive alternative to the traditional microscopic approach [12, 13]. Endoscopy offers enhanced visualization, particularly in anatomically restricted areas such as the cerebellopontine angle. However, the clinical superiority of endoscopy over traditional microscopy remains under debate. Beyond TN and HFS, MVD has been employed in other conditions, broadening its clinical utility. For instance, it has been used in treatment-resistant cases of vestibular paroxysmia and pulsatile tinnitus caused by vascular compression of the vestibulocochlear or cochlear nerves, though outcomes remain mixed [14, 15]. Additionally, early studies have explored its role in addressing refractory hypertension caused by neurovascular compression of the rostral ventrolateral medulla, with promising initial results [16].

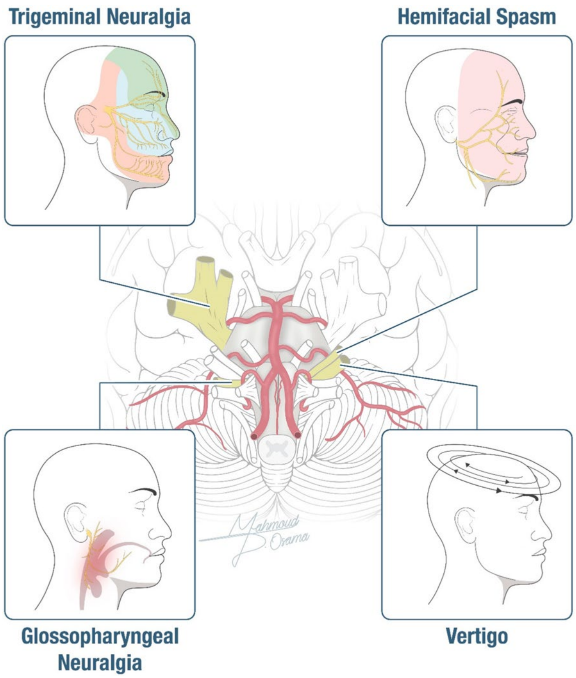


Fig. 1 Conditions Treated by Microvascular Decompression Surgery (This figure highlights the primary neurological conditions addressed by MVD surgery, including trigeminal neuralgia, hemifacial spasm, glossopharyngeal neuralgia, and vertigo. These disorders are caused by blood vessels compressing the nerves, leading to debilitating symptoms. MVD alleviates these conditions by relieving vascular compression on the affected cranial nerves, thus providing symptom relief)

Clinical outcomes of MVD are generally favorable. Studies report high success rates, with many patients experiencing immediate and significant symptom relief [17]. However, the procedure is not without risks, including hearing loss, facial numbness, and pain recurrence. Long-term follow-up studies reveal that while MVD provides substantial relief, some patients may experience recurrent symptoms requiring further intervention [18]. Despite these challenges, MVD continues to be heralded as the gold standard surgical intervention for cranial nerve compression disorders.

Imaging plays a pivotal role in diagnosing neurovascular compression and planning MVD [19]. High-resolution three-dimensional (3D) MRI, particularly 3D-FIESTA and 3D-TOF MRA, has demonstrated high sensitivity (97.4%) and specificity (100%) in identifying neurovascular conflicts, thereby enabling precise surgical planning [20]. These imaging modalities not only offer precise anatomical depictions of the offending vessels, but also enable prognostic evaluation. Advances in imaging technology have enhanced the diagnostic accuracy and preoperative planning for MVD, enabling surgeons to address complex neurovascular relationships effectively [20].

Furthermore, innovative techniques continue to expand the scope of MVD. For instance, the biomedical glue sling technique offers a simple yet effective solution for trigeminal neuralgia caused by an atherosclerotic vertebrobasilar artery, providing complete decompression [21]. These advancements underscore the ongoing evolution of MVD techniques, catering to a broader spectrum of clinical scenarios.

This review aims to provide an updated synthesis of the historical milestones, recent advances, and emerging techniques in MVD. By offering critical insights into the evolution and applications of this valuable surgical procedure, the study seeks to highlight its importance in improving patient outcomes and addressing diverse cranial nerve disorders.

Methods

Literature search strategy

A comprehensive literature search was conducted across multiple reputable databases to thoroughly examine the historical development and recent advancements in MVD. The search strategy was meticulously refined to ensure inclusivity and relevance. Keywords were combined using Boolean operators (AND, OR) to enhance specificity, and the search was restricted to peer-reviewed papers, systematic reviews, and clinical trials published in English between 1970 and 2024. This timeframe was chosen to encompass both foundational studies and contemporary innovations in MVD. The databases included PubMed, Google Scholar, SpringerLink, BioMed Central, Scopus, and ScienceDirect.

The search terms used were "microvascular decompression," "history of microvascular decompression," "trigeminal neuralgia," "glossopharyngeal neuralgia," "Jannetta procedure," "endoscopic microvascular decompression," "tentorial sling technique," and "hemifacial spasm." Inclusion criteria required studies that addressed the history, techniques, procedures, outcomes, and advancements in MVD. Only peer-reviewed articles in English, comprehensive reviews, meta-analyses, and clinical trials with robust methodologies were included. Exclusion criteria encompassed studies without full-text availability, those unrelated to MVD or focused on alternative surgical procedures, and case reports or case series with fewer than five patients. Furthermore, studies published before 1970 were excluded to maintain focus on the period marked by the introduction of the Jannetta procedure, which established a new standard for surgical practice.

Titles and abstracts were screened to filter irrelevant studies, and potentially relevant full-text manuscripts were retrieved for further evaluation. Eligibility was assessed according to the inclusion and exclusion criteria. Additionally, the reference lists of selected studies were reviewed to identify further relevant articles, ensuring a comprehensive and exhaustive literature review.

Data collection

The data collection process involved a thorough and rigorous extraction of pertinent information from the selected studies. To ensure accuracy and mitigate bias, two independent reviewers carefully evaluated each paper. The extracted data encompassed study characteristics, research designs, sample sizes, follow-up periods, and patient demographics, as well as specific diagnoses such as trigeminal neuralgia, hemifacial spasm, or glossopharyngeal neuralgia. Surgical techniques were analyzed in detail, including descriptions of traditional microscopic MVD, endoscopic MVD, and adjunctive procedures. Outcome measures, complication rates, recurrence rates, and patient-reported outcomes, such as pain relief and quality of life metrics, were also documented. Particular emphasis was placed on studies with robust methodologies and long-term follow-up data. Observational studies and clinical trials were rigorously analyzed to ensure high methodological quality. Discrepancies between the two reviewers during data extraction were resolved through discussion or consultation with a third reviewer. The extracted data were synthesized by categorizing studies based on their primary focus areas, such as historical evolution, technical innovations, or clinical outcomes. This systematic approach ensured the inclusion of comprehensive and detailed information, facilitating an in-depth analysis of MVD's historical and contemporary advancements.

Surgical techniques

Standard MVD procedure

This section provides a detailed overview of the microvascular decompression (MVD) procedure, emphasizing the key guiding principles (Fig. 2).

Patient positioning

The procedure begins with the administration of general anesthesia and endotracheal intubation. The patient is positioned in the lateral decubitus position, which offers several advantages. This positioning facilitates intraoperative lumbar needle placement for cerebrospinal fluid (CSF) drainage and frees the ipsilateral shoulder from the operative field.

Incision

The incision landmark is a line adjoining an imaginary trajectory extending from the mastoid groove to the

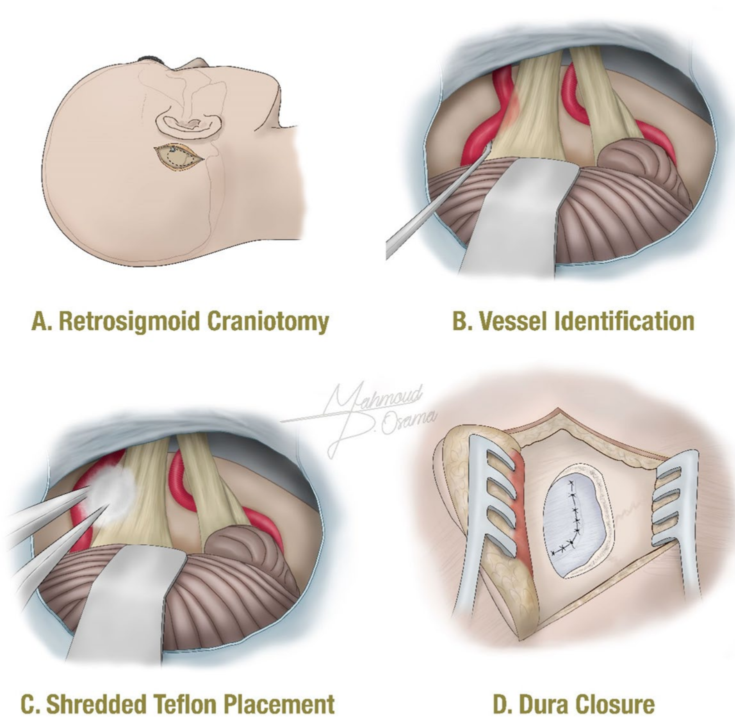


Fig. 2 Overview of Microvascular Decompression Surgical Procedure (This figure illustrates the key steps of the microvascular decompression (MVD) procedure. The process involves gaining access to the affected cranial nerve, identifying the blood vessel causing compression, and placing shredded Teflon to relieve pressure. The surgery concludes with proper closure of the dura and surgical site)

zygoma. Various incision techniques have been described in the literature, each with distinct advantages and disadvantages. For instance, Jannetta preferred a linear incision in his series, while Walter Dandy employed a reverse U-incision [22]. While a linear incision allows for quick access and reduces scarring, it may increase the risk of injury to the occipital neurovascular complex. Consequently, alternative incisions such as the modified U-incision, C-shaped incision, and hockey stick incision have been developed.

The length of the incision varies depending on the cranial nerve involved. For example:

- A '5–6-4' incision (5 mm medial, 6 cm above, and 4 cm below the medial notch) is used for decompression of the trigeminal nerve (CN V).
- A '5–5-5' incision is used for the facial and vestibulocochlear nerves (CNs VII and VIII).
- A '5–4-6' incision is used for glossopharyngeal nerve (CN IX) decompression [23].

The incision is developed down to the skull with meticulous care to avoid injury to the occipital artery, followed by the placement of cerebellar retractors.

Bone work

A burr hole is created at the inferomedial aspect of the junction of the sigmoid and transverse sinuses, which serves as the superior limit of the craniectomy. The craniectomy is then fashioned with a 2 cm diameter using a Kerrison rongeur, ensuring the tip points away from the sinus to avoid injury. In elderly patients, where the dural sinus wall may adhere to the bone, a dural separator is used before employing rongeurs [22]. If mastoid air cells are breached, they are promptly sealed with bone wax to prevent complications such as CSF leakage, meningitis, or air embolism.

Surgical access

A careful durotomy is performed with margins along the sinuses, taking precautions to avoid extending into the sinus. The dural edges are retracted using stay sutures to ensure adequate exposure to the surgical corridor. Cisternostomy and CSF drainage are performed to achieve brain relaxation. Additional techniques, such as lumbar drainage, osmotherapy with mannitol, or hyperventilation, may also be utilized to facilitate brain relaxation.

Different approaches for different nerve involvement

At this stage, an operating microscope is used to enhance precision.

- Trigeminal Nerve (CN V):

The surgical trajectory targets the junction between the tentorium and the petrous bone. Dissection is performed carefully using cottonoids, with minimal cerebellar retraction over a rubber dam, as described by Jannetta. Preservation of neurovascular structures is prioritized, although the superior petrosal vein may occasionally need to be sacrificed. A comprehensive 360-degree inspection of the nerve's intracranial course is conducted, focusing on the root entry zone, the most common site of vascular compression. The offending vessel is mobilized, and smaller veins are cauterized and divided to prevent recanalization. A Teflon patch soaked in saline is used to isolate the nerve from the compressive vessel [22].

- Trigeminal Nerve (CN V):

These nerves are located anterior to the flocculus, with the vestibulocochlear nerve situated posteriorly and slightly lateral to the facial nerve. Minimal superomedial retraction and partial excision of the flocculus may be necessary for optimal exposure. Intraoperative brainstem auditory-evoked potentials are utilized to monitor and prevent postoperative hearing loss.

- Glossopharyngeal Nerve (CN IX):

This nerve is traced from its exit at the jugular foramen, and the surgical field is adjusted accordingly for adequate decompression.

Closure

The operative field is thoroughly irrigated with saline, and watertight dural closure is performed to minimize the risk of CSF leakage and pseudomeningocele formation. In his series, Cohen-Gadol achieved favorable outcomes with a leakage rate of only 1% by approximating the dura without using additional sealing techniques [22]. Bone edges are waxed, and cranioplasty is performed to restore structural integrity. The surgical wound is then closed in layers to ensure proper healing.

Recent advances: innovations and improvements in surgical techniques and technologies

Advances in MVD encompass nearly every aspect of the surgical technique, reflecting the ongoing evolution of neurosurgical practices. Early innovations included the choice of interposition agents, transitioning from the use of muscle by early pioneers to synthetic sponges like polyvinyl formyl alcohol foam, Ivalon, and Teflon. However, the use of these agents has been associated with complications such as granuloma formation and recurrence of symptoms due to their compressive effects [24]. Fukushima introduced the vascular sling transposition technique, which uses sling retraction to relieve neurovascular compression. Subsequent advancements have expanded on this method, incorporating materials such as aneurysm clips, Gore-Tex tape, Dacron sutures, Teflon pieces, glue-coated slings, and fascia strips to manage offending vessels [24, 25]. Despite these innovations, studies demonstrating the efficacy of the sling retraction technique are often limited to small patient cohorts. Furthermore, comparative long-term outcome data between interposition and sling retraction approaches remain sparse, underscoring the need for more extensive research [25]. The progression from binocular microscopes with a 250 mm objective lens to endoscope-assisted microscopy has culminated in the development of fully endoscopic MVD, first described by Jarrahy in 2002 [26, 27].

Endoscopic MVD provides improved illumination and panoramic visualization, enabling surgeons to navigate complex neurovascular conflicts with greater clarity. Studies by Yu et al. and Peng et al. highlight that endoscopic MVD is particularly advantageous in addressing deep-seated or angled lesions, where traditional microscopic visualization may be limited [12, 13]. Additionally, Yun et al. reported comparable rates of symptom relief and complication profiles between endoscopic and traditional microscopic MVD, with potential benefits of shorter operative times and smaller craniectomy sizes [28]. Nonetheless, critics argue that enhanced visibility offered by endoscopic techniques does not inherently equate to improved surgical precision, which remains more dependent on surgeon skill and the quality of intraoperative tools than on the imaging modality alone [29]. Furthermore, the adoption of endoscopic MVD necessitates specialized equipment and extensive training, posing a significant learning curve for surgeons transitioning from conventional methods. The current lack of high-quality comparative studies limits the ability to definitively assess whether the enhanced visualization provided by endoscopic MVD translates into superior precision or long-term outcomes. In addition to endoscopic innovations, there is a growing trend in the application of three-dimensional (3D) exoscope-assisted MVD, which provides surgeons with advanced visualization tools while potentially mitigating some of the challenges associated with fully endoscopic techniques (Fig. 3) [30].

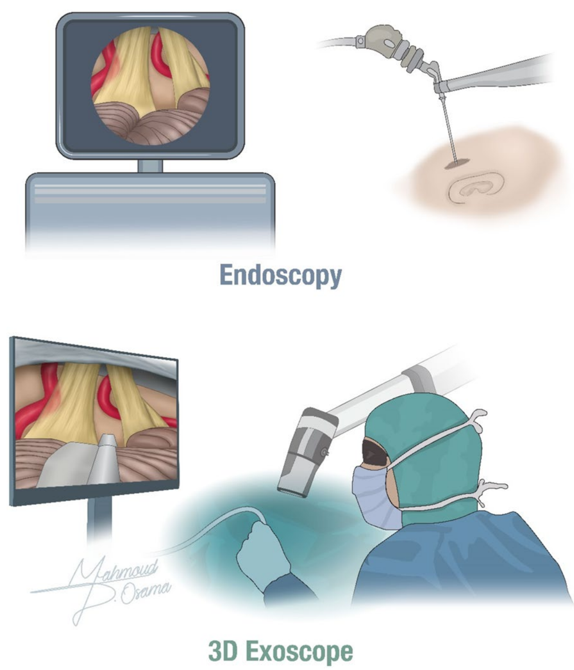


Fig. 3 Technological Advancements in Microvascular Decompression Surgery (Recent innovations have significantly enhanced microvascular decompression procedures. Endoscopy offers improved visualization of the nerve–vessel relationship through minimally invasive techniques. The 3D exoscope delivers high-definition, magnified views of the surgical site, further refining the precision of surgical interventions)

Comparative analysis

A comparative evaluation of clinical efficacy between newer interposition agents, Ivalon and Teflon, was conducted to assess postoperative outcomes. A multicenter study by Pressman et al. demonstrated that Ivalon was associated with a higher incidence of temporary postoperative hearing loss compared to Teflon, although both agents exhibited similar relapse rates [31]. Owashi and colleagues compared interposition techniques and reported a higher rate of early spasm relief in the interposition group. However, there were no significant differences in recurrence or complication rates between the groups [32]. In terms of surgical approaches, Villamil and colleagues conducted a retrospective cohort study that revealed comparable postoperative pain outcomes between patients treated with microscopic and fully endoscopic MVD. Interestingly, patients in the endoscopic group experienced shorter hospital stays. Shu and colleagues reported similar findings, further supporting the potential advantages of the endoscopic approach in reducing recovery time [13, 26, 28, 33].

Clinical outcomes

MVD has firmly established itself as the gold standard for treating cranial nerve compression disorders, particularly TN, HFS, and GPN. With decades of clinical experience, numerous studies affirm MVD's efficacy, particularly in providing immediate and substantial symptom relief. For TN, MVD demonstrates remarkable success, with 80–90% of patients reporting significant pain relief shortly after surgery [34]. Long-term studies further reinforce these outcomes, showing 70–80% of patients remaining pain-free at five years [34]. However, symptom recurrence occurs in approximately 15–25% of patients within ten years [35]. Similarly, MVD achieves high success rates for HFS, with over 90% of patients experiencing immediate cessation of spasms and long-term relief sustained in the majority of cases [36]. While recurrence is a recognized challenge, it does not undermine the overall effectiveness of MVD. Factors such as the surgeon's expertise, the complexity of neurovascular conflicts, and the presence of multiple compressive vessels are significant predictors of long-term success [34]. Patients with complex anatomical presentations or less meticulous surgical interventions face a higher risk of recurrence. Repeat MVD, although effective, achieves lower success rates than initial procedures, typically ranging between 50 and 60% [34]. These findings underscore the importance of careful patient selection and comprehensive preoperative planning, including detailed imaging studies to delineate the exact nature and extent of neurovascular compression.

Although MVD is widely regarded as a safe and effective procedure, it is not without risks. The most common complications include cerebrospinal fluid (CSF) leakage, hearing loss, facial numbness, and cranial nerve damage.

CSF Leakage

CSF leakage, a significant complication, occurs in approximately 2–4% of cases [4]. The advent of calcium phosphate cement cranioplasty has emerged as a robust solution, significantly reducing CSF leakage compared to traditional reconstruction materials such as polyethylene titanium mesh [37]. This technique leverages the osteoconductive properties of calcium phosphate cement to create a watertight seal at the surgical site, minimizing associated complications like pseudomeningocele formation [38]. Retrospective studies reveal significantly lower rates of wound infection (0.6%) and CSF leaks (0%) with calcium phosphate cement compared to titanium mesh cranioplasty, which reported rates of 5.4% and 6%, respectively [39]. In retrosigmoid craniotomies, the use of calcium phosphate cement has demonstrated a statistically significant reduction in CSF leak rates and pseudomeningocele formation as well as favorable cosmetic outcomes compared to non-cement closures [40, 41]. Furthermore, the safety profile of calcium phosphate cement cranioplasty extends to other skull base surgeries, such as vestibular schwannoma resections, where CSF leak rates were reduced to as low as 1% [42]. These findings highlight the essential role of calcium phosphate cement in modern neurosurgical practice, making it a preferred option for cranioplasty during MVD.

Hearing loss

Hearing loss, particularly in HFS patients, occurs in approximately 1–2% of cases due to the proximity of the auditory nerve to the surgical field [43, 44]. Fixed cerebellar retraction has been identified as a significant risk factor for postoperative high-frequency hearing loss [33]. Greater retraction depth correlates with a higher incidence of hearing complications, emphasizing the importance of minimizing or avoiding fixed retraction [45]. Techniques such as preserving the arachnoid membrane along the eighth cranial nerve and limiting the duration of microscopic manipulation significantly reduce auditory complications [43]. The use of intraoperative brainstem auditory evoked potential (BAEP) monitoring provides real-time feedback, enabling surgeons to identify and mitigate excessive retraction that could result in permanent hearing loss [46]. For instance, delays in BAEP Peak V latency exceeding 1 ms serve as critical warning thresholds requiring immediate surgical adjustments to protect auditory function [46].

Facial numbness

Facial numbness, though less common with modern techniques, remains a potential risk for TN patients. This complication ranges from mild to severe and is sometimes accompanied by paresthesia. Fully endoscopic MVD has shown potential advantages in enhancing intraoperative visualization. The panoramic view provided by endoscopy facilitates the identification of neurovascular conflicts in challenging regions, which may remain obscured with traditional microscopy [12, 47]. While early studies suggest that endoscopic MVD provides comparable clinical outcomes to microscopic MVD, including effective pain relief and low complication rates, high-quality evidence substantiating its superiority remains limited [28, 29]. Endoscopic MVD offers advantages such as smaller craniectomy sizes, reduced tissue retraction, shorter operative times, and faster recovery [48, 49]. However, variability in outcomes underscores the need for large-scale randomized controlled trials to definitively evaluate the efficacy and safety of endoscopic versus traditional techniques.

Global disparities in MVD outcomes

The outcomes of MVD vary significantly between wealthy and resource-limited countries, primarily due to differences in healthcare infrastructure, access to advanced technologies, and the availability of skilled neurosurgeons. Wealthy nations benefit from advanced imaging modalities like high-resolution MRI and MR angiography, facilitating accurate identification of neurovascular conflicts and contributing to higher success rates and lower complication rates [50]. In contrast, resource-limited settings often lack access to these advanced technologies, leading to delayed diagnoses and suboptimal surgical outcomes [50]. The scarcity of specialized neurosurgeons and inadequate postoperative care further exacerbates complications and recurrence rates. Global health initiatives, such as surgeon training programs, affordable imaging solutions, and telemedicine, play a crucial role in bridging these disparities. By improving access to high-quality surgical care, these efforts hold promise for enhancing MVD outcomes worldwide [50].

Technical and technological innovations

While performing a novel surgical technique, Jannetta observed an artery cross-compressing the nerve and stated, "That is the cause of the tic" [6, 51]. Since then, numerous surgical refinements and technological advancements have been introduced to reduce morbidity and enhance the efficacy of this procedure. From basic surgical refinements to the integration of robotics, even simple improvements can result in impactful changes. For example, optimizing the MVD procedure involves ensuring the correct operating room setup, precise patient positioning, recognition of anatomical landmarks, detailed intraoperative inspections, and a commitment to achieving perfect results [22, 52]. These foundational elements contribute to further research on refining techniques, ranging from incision and approach types to cerebellar and meningeal management [53, 54].

Neuromonitoring

Neuromonitoring has become a standard tool for evaluating neurological function during surgery. Blue and colleagues described its use in HFS treated with an endoscopic technique, where intraoperative monitoring of the lateral spread response in the buccal and mandibular branches provided critical real-time feedback on the surgery's safety and efficacy [55]. This innovation underscores the role of neuromonitoring in reducing complications and enhancing surgical outcomes.

Endoscopic assistance

Over time, endoscopic assistance in MVD has gained traction due to its minimally invasive nature, enhanced panoramic visualization, reduced need for brain and cerebellar retraction, and shorter operative times [12, 47]. Although some studies suggest a lower recurrence rate with endoscopic techniques, evidence remains inconclusive, as many reports indicate similar recurrence and complication rates between endoscopic and microscopic approaches [28, 29]. The endoscope primarily improves visualization of hidden anatomical regions and facilitates the management of complex neurovascular conflicts. However, its use requires specialized equipment and extensive training, presenting a steep learning curve for surgeons [48, 56]. Future comparative studies are needed to better define the role of endoscopic techniques in advancing MVD.

Neuronavigation and imaging

Technological innovations have also advanced imaging techniques used in conjunction with MVD. Traditional two-dimensional (2D) methods, such as computed tomographic angiography (CTA) and magnetic resonance angiography (MRA), have evolved into more sophisticated neuronavigation systems. These systems integrate imaging modalities to form artificial intelligence (AI)-assisted three-dimensional (3D) models, enabling highly accurate preoperative planning [56, 57]. The fusion of imaging modalities creates virtual and augmented reality environments, allowing surgeons to visualize 3D images overlaid directly onto real anatomical structures. This real-time navigation capability eliminates the need for frequent image-checking pauses, reducing surgical errors and enhancing procedural efficiency [10, 58]. For example, MVDNet, a deep neural network (DNN), contributes to real-time segmentation of vessels and nerve structures during surgery, further minimizing complications [59].

Artificial Intelligence (AI) and Prognostic Tools

Emerging evidence suggests that AI and DNN technologies may extend beyond intraoperative assistance to postoperative functionalities. For instance, Hao's study demonstrated the potential of these technologies in predicting pain prognosis after MVD surgery by identifying key predictors. This predictive capability is critical for early intervention, ultimately reducing morbidity and improving long-term outcomes [60].

Future technologies

The integration of innovative tools continues to shape the future of MVD. For example, the 3D Exoscope is a cutting-edge tool that has recently gained attention as a potential replacement for the traditional microscope in MVD procedures. Khalifeh and colleagues demonstrated its ability to enhance surgical visualization while maintaining ergonomic advantages for the surgeon (Fig. 3) [61]. However, further research and testing are required to evaluate the risks and benefits associated with this novel technology.

Recurrence rate

The initial success rate of MVD for TN is reported to range between 80 and 95%, with many patients experiencing immediate and substantial pain relief following surgery [41]. However, recurrence rates vary depending on the duration of follow-up and are generally reported to be between 10 and 30% [62]. A 15-year study conducted by Zakrzewska et al. found a recurrence rate of approximately 30% [63]. While recurrence often occurs within the first five years postoperatively, late recurrences have also been observed. Factors contributing to recurrence include incomplete decompression, residual neurovascular compression, atypical pain presentations, comorbidities such as multiple sclerosis, and vascular changes over time [64]. For HFS, MVD achieves an initial success rate between 85 and 95%, with most patients reporting significant symptom relief shortly after surgery [65]. Recurrence rates for HFS are generally lower than those for TN, ranging from 5 to 15% [66]. In a long-term study, Sekula et al. reported a recurrence rate of approximately 8% at five years [67]. Factors associated with recurrence in HFS include improper positioning or displacement of decompressive material, progressive vascular changes, incomplete resolution of neurovascular compression, and recurrent venous compression, which presents unique challenges for surgical management [68]. For GPN, MVD typically achieves a high initial success rate of 85% to 95%. However, recurrence patterns are less well-documented due to the rarity of this condition. Recurrence rates are estimated to range from 5 to 20%, with most cases occurring within the first few years after surgery. Contributors to recurrence include insufficient decompression, anatomical vascular changes over time, or nerve injury sustained during the surgical procedure [69, 70].

Future directions

MVD has established itself as a highly effective treatment for TN and other cranial nerve compression disorders. However, the procedure is not without limitations, and several gaps in research remain. While MVD often provides significant pain relief, the duration of its efficacy varies, with some patients experiencing relief for several years while others report recurrence within months. Additionally, adverse effects, such as facial numbness ranging from severe hypesthesia to a pins-and-needles sensation, occur in 3–30% of cases [18, 68]. Long-term follow-up studies are essential to better understand these recurrence rates and mitigate side effects. Common postoperative complications, including CSF leakage, facial hypesthesia, and hearing loss, warrant further investigation. More robust studies are needed to develop preventive measures and improve postoperative outcomes [67]. Although recent studies have compared classic microsurgical and fully endoscopic MVD techniques, longer and more sophisticated investigations are necessary to determine which approach is superior in terms of efficacy, safety, and long-term results [13]. The expertise and skill level of surgeons play a crucial role in MVD outcomes. Research should focus on standardized training protocols to improve success rates across diverse healthcare systems [71]. Additionally, debates regarding the use of fibrin versus Teflon as interposition materials highlight the need for further studies to evaluate their effectiveness, biocompatibility, and long-term impacts.

Advancements in imaging and visualization

Future trends in MVD are centered on the integration of advanced imaging technologies to enhance surgical precision. Innovations such as three-dimensional (3D) imaging and augmented reality (AR) in MVD procedures, combined with high-resolution CT and MRI, provide surgeons with detailed anatomical visualization during surgery. Studies are needed to assess the impact of AR and 3D imaging on surgical outcomes [72]. Fusion imaging techniques, such as combining magnetic resonance cisternography and angiography, have emerged as essential tools for preoperative simulation and visualization of neurovascular relationships. These technologies facilitate the precise identification of compression sites and provide surgeons with a virtual roadmap of the neurovascular anatomy [73]. For instance, fusion imaging enables a multi-perspective analysis of the trigeminal nerve root entry zone, correlating closely with intraoperative findings [74]. Emerging technologies, such as virtual reality (VR) planning, offer additional promise by improving preoperative visualization and surgical outcomes [75]. VR enhances patient satisfaction by enabling surgeons to achieve greater accuracy during planning and execution. Intraoperative imaging tools, such as indocyanine green (ICG) angiography, provide real-time confirmation of successful decompression, contributing to greater surgical safety and efficacy [76, 77].

Robotic-Assisted MVD

Although MVD and endoscopic techniques have been widely studied, there is limited information on robotic-assisted MVD for TN and HFS. One study reported that robotic surgery improved accuracy by introducing steady, precise movements, thereby reducing human error [78, 79]. Robotic-assisted surgery holds the potential to revolutionize MVD by enhancing surgical precision and outcomes. However, FDA approval is still pending due to the lack of specialized instruments required for robotic MVD procedures. Further research and testing are essential to expand the use of robotic-assisted surgery for various cranial nerve disorders.

Artificial intelligence and gene therapy

AI and machine learning are increasingly being utilized in the diagnosis and treatment of TN. For instance, MVDNet, a deep learning model, has demonstrated remarkable precision in real-time segmentation of blood vessels and cranial nerves during MVD operations for TN and facial nerve problems [80–82]. Such technologies hold promise for minimizing intraoperative complications and optimizing surgical outcomes.

A recent review synthesized findings from approximately 345 articles, of which 12 were selected and included, focusing on the expression of ionotropic channels, reactive oxygen species, inflammatory markers, and microRNAs. Of these 12 articles, only 4 reported studies conducted in animal models investigating the corresponding TN mechanism observed in humans [83].

Moreover, gene therapy represents an emerging frontier in TN treatment. KRIYA-748, a novel gene therapy currently under development, aims to address the molecular underpinnings of TN [82, 84, 85]. Future research into the genetic and molecular pathways of TN may pave the way for targeted therapies that could complement or even replace traditional MVD.

Conclusion

This paper highlights advancements in MVD for TN, HFS, and GN, focusing on the potential of technologies like endoscopes, exoscopes, deep neural networks, augmented reality, and robotics to enhance visualization, improve precision, reduce complications, and optimize patient outcomes. The importance of surgeon expertise and standardized protocols in achieving consistent success rates is also emphasized. Additionally, innovations such as AI, gene therapies and advanced imaging techniques offer promising alternatives for managing cranial nerve compression disorders. Continued research is crucial to validate the long-term safety and efficacy of these approaches, ensuring their integration into clinical practice and expanding access to cutting-edge care worldwide.

Abbreviations

MVD	Microvascular decompression
TN	Trigeminal neuralgia
HFS	Hemifacial spasm
GPN	Glossopharyngeal neuralgia
MRI	Magnetic resonance imaging
CSF	Cerebrospinal fluid
CTA	Computed tomographic angiography
OR	Operating room
MRA and MRV	Magnetic resonance angiography and venography
2D	Bidimensional
3D	Three-dimensional
DNN	Deep neural network
CT	Computed tomography
3D	3 Dimensional
AR	Augmented reality
FDA	Food and Drug Administration
MVDNet	Microvascular decompression network
CN	Cranial nerve

Acknowledgements
None.

Authors' contributions
I.I.O: conceptualized, designed, project administration; S.S.M., and I.I.O: validation; M.O: wrote, edited, and prepared the illustrations of the manuscript; A.G.R: methodology; I.I.O., S.S.M., M.A., L.F.F.P., M.D.S., C.O.E., Y.R., J.D.R.S., N.M.P., A.G.R., U.I., D.D.O., I.M.A., I.A., O.K.: collected the data, wrote, reviewed, and revised the manuscript; I.I.O. M.K., B.C., M.Y.F., F.S.P., D.E.L: critically reviewed, supervised the study; and all the authors read and approved the final version of the manuscript.

Funding
None.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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Received: 5 November 2024 Accepted: 2 January 2025
Published online: 11 January 2025

References

1. Burchiel KJ, Slavin KV. On the natural history of trigeminal neuralgia. Neurosurgery. 2000;46(1):152–4 (discussion 154-155).

2. Burchiel KJ. Microvascular decompression for trigeminal neuralgia. J Neurosurg. 2008;108(4):687–8. https://doi.org/10.3171/JNS/2008/108/4/0687.
3. Simms HN, Honey CR. The importance of autonomic symptoms in trigeminal neuralgia Clinical article. J Neurosurg. 2011;115(2):210–6. https://doi.org/10.3171/2011.4.JNS101843.
4. McLaughlin MR, Jannetta PJ, Clyde BL, Subach BR, Comey CH, Resnick DK. Microvascular decompression of cranial nerves: Lessons learned after 4400 operations. J Neurosurg. 1999;90(1):1–8. https://doi.org/10.3171/jns.1999.90.1.0001.
5. Patel SK, Markosian C, Choudhry OJ, Keller JT, Liu JK. The historical evolution of microvascular decompression for trigeminal neuralgia: from Dandy's discovery to Jannetta's legacy. Acta Neurochir (Wien). 2020;162(11):2773–82. https://doi.org/10.1007/s00701-020-04405-7.
6. Kaufmann AM, Price AV. A history of Jannetta procedure. J Neurosurg. 2020;132(2):639–46. https://doi.org/10.3171/2018.10.Jns181983.
7. Jannetta PJ. Treatment of trigeminal neuralgia by suboccipital and transtentorial cranial operations. Clin Neurosurg. 1977;24:538–49. https://doi.org/10.1093/neurosurgery/24.cn_suppl_1.538.
8. Jannetta PJ, McLaughlin MR, Sekula RF Jr. Microvascular decompression. Oxford: Trigeminal neuralgia New York; 2011. p. 192–213.
9. Chen L, Shang Y, Zhang Y, Zhao Y. Endoscopic microvascular decompression versus microscopic microvascular decompression for trigeminal neuralgia: a systematic review and meta-analysis. J Clin Neurosci. 2023;117:73–8.
10. Wang J, Zhang W, Wang X, Luo T, Wang X, Qu Y. Application of Neuronavigation in Microvascular Decompression: Optimizing Craniotomy and 3D Reconstruction of Neurovascular Compression. J Craniofacial Surg. 2023;34(7)
11. Legninda Sop FY, D'Ercole M, Izzo A, et al. The Impact of Neuronavigation on the Surgical Outcome of Microvascular Decompression for Trigeminal Neuralgia. World Neurosurg. 2021;149:80–5. https://doi.org/10.1016/j.wneu.2021.02.063.
12. Yu G, Leng J, Xia Y, Min F, Xiang H. Microvascular decompression: Diversified of imaging uses, advantages of treating trigeminal neuralgia and improvement after the application of endoscopic technology. Front Neurol. 2022;13:1018268. https://doi.org/10.3389/fneur.2022.1018268.
13. Peng W, Zhao R, Guan F, et al. Fully endoscopic microvascular decompression for the treatment of hemifacial spasm, trigeminal neuralgia, and glossopharyngeal neuralgia: a retrospective study. BMC Surg. 2023;23(1):331. https://doi.org/10.1186/s12893-023-02214-0.
14. Liu F, Wei C, Huang W. Clinical long-term observation of the keyhole microvascular decompression with local anesthesia on diagnosis and treatment of vestibular paroxysmia. Acta Otolaryngol. 2020;140(5):378–82. https://doi.org/10.1080/00016489.2020.1723808.
15. Juan JS, Basura GJ. Tinnitus management in lateral skull base lesions. J Neurol Surg B Skull Base. 2019;80(2):125–31. https://doi.org/10.1055/s-0038-1676308.
16. Sun C, Zhu W, Zhang X, et al. Is MVD the effective treatment for poorly controlled hypertension? J Clin Neurosci. 2021;86:20–5. https://doi.org/10.1016/j.jocn.2021.01.015.
17. Holste K, Chan AY, Rolston JD, Englot DJ. Pain outcomes following microvascular decompression for drug-resistant trigeminal neuralgia: a systematic review and meta-analysis. Neurosurgery. 2020;86(2):182–90. https://doi.org/10.1093/neuros/nyz075.
18. Wang X, Wang H, Chen S, et al. The long-term clinical outcomes of microvascular decompression for treatment of trigeminal neuralgia compressed by the vertebra-basilar artery: a case series review. BMC Neurol. 2019;19(1):217. https://doi.org/10.1186/s12883-019-1450-z.
19. Xu R, Nair SK, Raj D, et al. The role of preoperative magnetic resonance imaging in assessing neurovascular compression before microvascular decompression in trigeminal neuralgia. World Neurosurg. 2022;168:e216–22. https://doi.org/10.1016/j.wneu.2022.09.092.
20. Leal PR, Hermier M, Souza MA, Cristino-Filho G, Froment JC, Sindou M. Visualization of vascular compression of the trigeminal nerve with high-resolution 3T MRI: a prospective study comparing preoperative imaging analysis to surgical findings in 40 consecutive patients who underwent microvascular decompression for trigeminal neuralgia. Neurosurgery. 2011;69(1):15–25. https://doi.org/10.1227/NEU.0b013e318212bafa. (discussion 26).
21. Liu J, Chen Z, Feng T, Jiang B, Yuan Y, Yu Y. Biomedical glue sling technique in microvascular decompression for trigeminal neuralgia caused by atherosclerotic vertebrobasilar artery: a description of operative technique and clinical outcomes. World Neurosurg. 2019;128:e74–80. https://doi.org/10.1016/j.wneu.2019.03.289.
22. Cohen-Gadol AA. Microvascular decompression surgery for trigeminal neuralgia and hemifacial spasm: naunces of the technique based on experiences with 100 patients and review of the literature. Clin Neurol Neurosurg. 2011;113(10):844–53. https://doi.org/10.1016/j.clineuro.2011.06.003.
23. Greenberg MS. Posterior fossa craniotomies. In: Greenberg's Handbook of Neurosurgery. 10th ed. New York: Thieme Medical Publishers; 2023. p. 1737–41.
24. Abougamil AB, Metwaly TI, Deif OA, Khedr W. Sling technique in microvascular decompression surgery for trigeminal neuralgia: early experience and functional outcomes. Egypt J Neurosurg. 2023;38(1):3. https://doi.org/10.1186/s41984-022-00183-9.
25. Masuoka J, Matsushima T, Kawashima M, Nakahara Y, Funaki T, Mineta T. Stitched sling retraction technique for microvascular decompression: procedures and techniques based on an anatomical viewpoint. Neurosurg Rev. 2011;34(3):373–80. https://doi.org/10.1007/s10143-011-0310-0.
26. Villamil F, Domecq Laplace L, Ruella ME, Caffaratti G, Monsalve M, Cervio A. [Endoscopic vs. microscopic techniques for the treatment of trigeminal neuralgia. Our experience at an Argentine care center]. Medicina (B Aires). 2023;83(4):579–587. Descompresión microvascular endoscópica versus microscópica en neuralgia trigeminal en un Centro argentino.
27. Jarrahy R, Cha ST, Eby JB, Berci G, Shahinian HK. Fully endoscopic vascular decompression of the glossopharyngeal nerve. J Craniofac Surg. 2002;13(1):90–5. https://doi.org/10.1097/00001665-200201000-00021.
28. Yun GY, Ahn JM, Park JH, Oh HJ, Shim JJ, Yoon SM. Preliminary report of fully endoscopic microvascular decompression. J Korean Neurosurg Soc. 2024;67(6):646–53. https://doi.org/10.3340/jkns.2024.0003.
29. Pak HL, Lambru G, Okasha M, et al. Fully endoscopic microvascular decompression for trigeminal neuralgia: technical note describing a single-center experience. World Neurosurg. 2022;166:159–67. https://doi.org/10.1016/j.wneu.2022.07.014.
30. Herta J, Rössler K, Dorfer C. Use of a 3D exoscope in microvascular decompression of the trigeminal nerve root. Neurosurg Focus Video. 2024;10(1):V14. https://doi.org/10.3171/2023.10.Focvid23149.
31. Pressman E, Hasegawa H, Farooq J, et al. Teflon versus ivalon in microvascular decompression for trigeminal neuralgia: a 2-center 10-year comparison. World Neurosurg. 2021;146:e822–8. https://doi.org/10.1016/j.wneu.2020.11.027.
32. Owashi E, Ohmura K, Shoda K, et al. Comparison of transposition and interposition methods in microvascular decompression for hemifacial spasm: an analysis of 109 cases performed by a single surgeon in a single-center retrospective study. Acta Neurochir (Wien). 2024;166(1):213. https://doi.org/10.1007/s00701-024-06111-0.
33. Shu W, Yang D, Ma K, et al. Endoscopic versus microscopic microvascular decompression for trigeminal neuralgia: a prospective controlled study. Pain Physician. 2024;27(1):E79–e88.
34. Lv MY, Deng SL, Long XF, Liu ZL. Long-term outcome of microvascular decompression for hemifacial spasm. Br J Neurosurg. 2017;31(3):322–6. https://doi.org/10.1080/02688697.2017.1297368.
35. Dewan MC, Rattani A, Fieggen G, et al. Global neurosurgery: the current capacity and deficit in the provision of essential neurosurgical care. Executive Summary of the Global Neurosurgery Initiative at the Program in Global Surgery and Social Change. J Neurosurg. 2019;130(4):1055–64. https://doi.org/10.3171/2017.11.Jns171500.
36. Thirumala P, Frederickson AM, Balzer J, et al. Reduction in high-frequency hearing loss following technical modifications to microvascular decompression for hemifacial spasm. J Neurosurg. 2015;123(4):1059–64. https://doi.org/10.3171/2014.12.Jns141699.
37. Eseonu CI, Goodwin CR, Zhou X, et al. Reduced CSF leak in complete calvarial reconstructions of microvascular decompression craniectomies using calcium phosphate cement. J Neurosurg. 2015;123(6):1476–9. https://doi.org/10.3171/2015.1.Jns142102.
38. Wolfson DI, Magarik JA, Godil SS, et al. Bone cement cranioplasty reduces cerebrospinal fluid leak rate after microvascular decompression: a single-institutional experience. J Neurol Surg B Skull Base. 2021;82(5):556–61. https://doi.org/10.1055/s-0040-1715607.

39. Foster KA, Shin SS, Prabhu B, Fredrickson A, Sekula RF Jr. Calcium phosphate cement cranioplasty decreases the rate of cerebrospinal fluid leak and wound infection compared with titanium mesh cranioplasty: retrospective study of 672 patients. World Neurosurg. 2016;95:414–8. https://doi.org/10.1016/j.wneu.2016.02.071.
40. Bauman MM, Webb KL, Michaelcheck CE, et al. Use of Calcium Phosphate Bone Cement in Retrosigmoid Craniotomies Reduces Rates of Craniotomy Site CSF Leak and Pseudomeningocele: A Cohort Study and Meta-Analysis. J Neurol Surg B Skull Base. 2024;85(S 01):S359. https://doi.org/10.1055/s-0044-1780158.
41. Frederickson AM, Sekula RF Jr. The utility of calcium phosphate cement in cranioplasty following retromastoid craniectomy for cranial neuralgias. Br J Neurosurg. 2013;27(6):808–11. https://doi.org/10.3109/02688697.2013.776670.
42. Zhang L, Galaiya D, Jackson CM, et al. Bone cement internal auditory canal reconstruction to reduce CSF leak after vestibular schwannoma retrosigmoid approach. Otol Neurotol. 2021;42(8):e1101–5. https://doi.org/10.1097/mao.0000000000003215.
43. Amagasaki K, Watanabe S, Naemura K, Nakaguchi H. Microvascular decompression for hemifacial spasm: how can we protect auditory function? Br J Neurosurg. 2015;29(3):347–52. https://doi.org/10.3109/02688697.2014.1003033.
44. Barker FG 2nd, Jannetta PJ, Bissonette DJ, Larkins MV, Jho HD. The long-term outcome of microvascular decompression for trigeminal neuralgia. N Engl J Med. 1996;334(17):1077–83. https://doi.org/10.1056/nejm199604253341701.
45. Li N, Zhao WG, Pu CH, Yang WL. Correlation between cerebellar retraction and hearing loss after microvascular decompression for hemifacial spasm: a prospective study. World Neurosurg. 2017;102:97–101. https://doi.org/10.1016/j.wneu.2017.02.137.
46. Polo G, Fischer C, Sindou MP, Marneffe V. Brainstem auditory evoked potential monitoring during microvascular decompression for hemifacial spasm: intraoperative brainstem auditory evoked potential changes and warning values to prevent hearing loss--prospective study in a consecutive series of 84 patients. Neurosurgery. 2004;54(1):97–104. https://doi.org/10.1227/01.neu.0000097268.90620.07. (discussion 104-6).
47. Halpern CH, Lang SS, Lee JY. Fully endoscopic microvascular decompression: our early experience. Minim Invasive Surg. 2013;2013:739432. https://doi.org/10.1155/2013/739432.
48. Guan H, Li S, Wang X. Fully endoscopic microvascular decompression for trigeminal neuralgia: technical note and early outcomes. Neurosurg Rev. 2023;46(1):292. https://doi.org/10.1007/s10143-023-02188-w.
49. Bohman LE, Pierce J, Stephen JH, Sandhu S, Lee JY. Fully endoscopic microvascular decompression for trigeminal neuralgia: technique review and early outcomes. Neurosurg Focus. 2014;37(4):E18. https://doi.org/10.3171/2014.7.Focus14318.
50. Cheng J, Meng J, Lei D, Hui X. Repeat microvascular decompression for patients with persistent or recurrent trigeminal neuralgia: Prognostic factors and long-term outcomes. Medicine (Baltimore). 2019;98(18):e15167. https://doi.org/10.1097/md.0000000000015167.
51. Yue Y, Zhao ZR, Liu DC, et al. Life-threatening complications after microvascular decompression procedure: Lessons from a consecutive series of 596 patients. J Clin Neurosci. 2021;86:64–70. https://doi.org/10.1016/j.jocn.2021.01.014.
52. Jannetta PJ, Rand RW. Transtentorial retrogasserian rhizotomy in trigeminal neuralgia by microneurosurgical technique. Bull Los Angeles Neurol Soc. 1966;31(3):93–9.
53. Nurimanov C, Mammadinova I, Menlibayeva K, Kaliyev A, Makhambetov Y, Akshulakov S. The outcomes of microvascular decompression for primary trigeminal neuralgia: insights from a single-center experience and technical advancements. Front Surg. 2024;11:1378717. https://doi.org/10.3389/fsurg.2024.1378717.
54. Tomasello F, Esposito F, Abbritti RV, et al. Microvascular Decompression for Trigeminal Neuralgia: Technical Refinement for Complication Avoidance. World Neurosurg. 2016;94:26–31. https://doi.org/10.1016/j.wneu.2016.06.097.
55. Bond AE, Zada G, Gonzalez AA, Hansen C, Giannotta SL. Operative strategies for minimizing hearing loss and other major complications associated with microvascular decompression for trigeminal neuralgia. World Neurosurg. 2010;74(1):172–7. https://doi.org/10.1016/j.wneu.2010.05.001.
56. Zagzoog N, Attar A, Takroni R, Alotaibi MB, Reddy K. Endoscopic versus open microvascular decompression for trigeminal neuralgia: a systematic review and comparative meta-analysis. J Neurosurg. 2019;131(5):1532–40. https://doi.org/10.3171/2018.6.Jns172690.
57. Wei W, Liu Z, Zhang W, Wang Y, Chen M. Application of virtual endoscopy in microvascular decompression of trigeminal neuralgia. J Craniofac Surg. 2021;32(5):1696–9. https://doi.org/10.1097/scs.0000000000007347.
58. Tanrikulu L, Hastreiter P, Troescher-Weber R, Buchfelder M, Naraghi R. Intraoperative three-dimensional visualization in microvascular decompression. J Neurosurg. 2007;107(6):1137–43. https://doi.org/10.3171/JNS-07/12/1137.
59. Bai R, Liu X, Jiang S, Sun H. Deep Learning Based Real-Time Semantic Segmentation of Cerebral Vessels and Cranial Nerves in Microvascular Decompression Scenes. Cells. 2022;11(11) https://doi.org/10.3390/cells11111830
60. Hao W, Cong C, Yuanfeng D, et al. Multidata analysis based on an artificial neural network model for long-term pain outcome and key predictors of microvascular decompression in trigeminal neuralgia. World Neurosurg. 2022;164:e271–9. https://doi.org/10.1016/j.wneu.2022.04.089.
61. Khalifeh JM, Ahmed AK, Ishida W, et al. Initial institutional experience using a robotic arm-enabled 4K 3D exoscope in neurosurgical operations. Neurosurg Focus Video. 2024;10(1):V2. https://doi.org/10.3171/2023.10.Focvid23150.
62. Samii M, Günther T. Retrospective analysis of reoperations in neurosurgical patients. Acta Neurochir (Wien). 1994;127(1–2):49–54.
63. Zakrzewska JM, Linskey ME. Trigeminal neuralgia. BMJ Clin Evid. 2014;2014
64. Miller LE, Miller VM. Safety and effectiveness of microvascular decompression for treatment of hemifacial spasm: a systematic review. Br J Neurosurg. 2012;26(4):438–44.
65. Park JS, Park K. Operative Findings of over 5000 Microvascular Decompression Surgeries for Hemifacial Spasm: Our Perspective and Current Updates. Life. 2023;13(9). https://doi.org/10.3390/life13091904
66. Sun H, Wang X, Chen S, et al. Hemifacial spasm caused by venous compression: management strategies. Clin Neurol Neurosurg. 2014;124:142–7.
67. Sekula RF, Frederickson AM, Arnone GD, et al. Microvascular decompression for hemifacial spasm: a systematic review and meta-analysis. J Neurosurg. 2015;122(3):692–701.
68. Sindou M, Leston J, Howeidy T, Decullier E, Chapuis F. Micro-vascular decompression for primary Trigeminal Neuralgia (typical or atypical). Long-term effectiveness on pain; prospective study with survival analysis in a consecutive series of 362 *patients. Acta Neurochir (Wien).* 2006;148(12):1235–45; discussion 1245. https://doi.org/10.1007/s00701-006-0809-2
69. Patel A, Kassam A, Horowitz M, Chang YF. Microvascular decompression in the management of glossopharyngeal neuralgia: analysis of 217 cases. Neurosurgery. 2002;50(4):705–10. https://doi.org/10.1097/00006123-200204000-00004. (discussion 710-1).
70. Fayed ZY, Afify H. Long-term follow-up of microvascular decompression for management of trigeminal neuralgia. Egypt J Neurosurg. 2022;37(1):30. https://doi.org/10.1186/s41984-022-00171-z.
71. Jonas RA. Surgical experience makes a difference: but what is surgical experience? Eur J Cardiothorac Surg. 2021;60(1):113–4. https://doi.org/10.1093/ejcts/ezab082.
72. Tanrikulu L. Microscope-based augmented reality: a new approach in intraoperative 3d visualization in microvascular decompression? Cureus. 2024;16(6):e62417. https://doi.org/10.7759/cureus.62417.
73. Satoh T, Onoda K, Date I. Fusion imaging of three-dimensional magnetic resonance cisternograms and angiograms for the assessment of microvascular decompression in patients with hemifacial spasms. J Neurosurg. 2007;106(1):82–9. https://doi.org/10.3171/jns.2007.106.1.82.
74. Satoh T, Onoda K, Date I. Preoperative simulation for microvascular decompression in patients with idiopathic trigeminal neuralgia: visualization with three-dimensional magnetic resonance cisternogram and angiogram fusion imaging. Neurosurg. 2007;60(1):104–13. https://doi.org/10.1227/01.Neu.0000249213.34838.C9. (discussion 113-4).
75. Fabrig OD, Serra C, Kockro RA. Virtual reality planning of microvascular decompression in trigeminal neuralgia: technique and clinical outcome. J Neurol Surg A Cent Eur Neurosurg. 2024;85(6):585–93. https://doi.org/10.1055/s-0043-1777762.

76. Zhang H, Fu WM, Chen P, Shi J. Intraoperative indocyanine green angiography during microvascular decompression surgery: report of 30 cases. Acta Neurochir (Wien). 2014;156(8):1561–4. https://doi.org/10.1007/s00701-014-2105-x.
77. Kabulo KDM, Komatsu F, Sharafundeen A, et al. Use of indocyanine green angiography during endoscopic microvascular decompression for trigeminal neuralgia. Interdiscip Neurosurg. 2024;36:101900. https://doi.org/10.1016/j.inat.2023.101900.
78. Ji HK, Lee MH, Lee TK. Robotic surgery for microvascular decompression in hemifacial spasm: a feasibility study. Neurofunction. 2024;20(1):28–33. https://doi.org/10.52662/nf.2023.00108
79. Dong B, Xu R, Lim M. The pathophysiology of trigeminal neuralgia: a molecular review. J Neurosurg. 2023;139(5):1471–9. https://doi.org/10.3171/2023.2.JNS23274.
80. Battistelli M, Izzo A, D'Ercole M, D'Alessandris QG, Montano N. The role of artificial intelligence in the management of trigeminal neuralgia. Mini Review. Front Surg. 2023;10
81. Zuhair V, Babar A, Ali R, Oduoye MO, Noor Z, Chris K, Okon II, Rehman LU. Exploring the impact of artificial intelligence on global health and enhancing healthcare in developing nations. J Prim Care Commun Health. 2024;15:21501319241245850. https://doi.org/10.1177/21501319241245847.
82. Atewologun FA, Okesanya OJ, Okon II, Kayode HH, Ukoaka BM, Olaleke NO, Ogaya JB, Okikiola LA, Manirambona E, Lucero-Prisno Iii DE. Examining the potentials of stem cell therapy in reducing the burden of selected non-communicable diseases in Africa. Stem Cell Res Ther. 2024;15(1):253. https://doi.org/10.1186/s13287-024-03864-4.
83. Kriya Therapeutics. Neurology: Gene Therapy for Trigeminal Neuralgia. Sep 2024. Available from: https://kriyatherapeutics.com/pipeline/neurology/
84. Kumar A, Arsal SA, Iqbal U, Okon II. Letter to the Editor Regarding "Tailored Concept for Accurate Neuroendoscopy: A Comparative Retrospective Single-Centre Study on Image-Guided Neuroendoscopic Procedures." World Neurosurg. 2024;191:347. https://doi.org/10.1016/j.wneu.2024.07.141.
85. Shafqat MD, Okon II. Why are clinical trials of deep brain stimulation terminated? An analysis of clinicaltrials.gov (new version). Brain Spine. 2024;4:104137. https://doi.org/10.1016/j.bas.2024.104137.

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