OPEN

PRS GLOBAL OPEN

ORIGINAL ARTICLE

Peripheral Nerve

Use of Magnetic Resonance Neurography for Sensory Nerve Injuries of the Head and Neck

Merel H.J. Hazewinkel, MD*
Yenpo Lin, MD†‡
Tim Y. Li, BA*†
Babacar Cisse, MD, PhD§
Ek T. Tan, PhD†
Darryl B. Sneag, MD†
Lisa Gfrerer, MD, PhD*

Background: Identification of peripheral nerve injuries of the head and neck can be challenging due to a broad spectrum of symptoms from neuropathic pain to headaches and migraine. This article aimed to present the clinical features and diagnostic workup of patients with acute and chronic peripheral nerve injuries of the head and neck using magnetic resonance neurography (MRN), to demonstrate potential advantages compared with conventional magnetic resonance imaging (MRI).

Methods: Patients who presented with suspected peripheral nerve injury were either referred for a conventional MRI or MRN. Patients who underwent nerve exploration for suspected nerve transection and/or neuroma formation on imaging were included in this study. Imaging findings were correlated with intraoperative observations.

Results: Four patients (3 women, 1 man, age range: 34–70 years) were included. Three subjects had a history of head and neck surgery and 1 experienced direct trauma to the medial eyebrow. Clinical symptoms included numbness, allodynia, positive Tinel sign, and pain relief following nerve blocks. Two patients underwent conventional MRI and 2 underwent MRN. MRI provided a vague indication of potential neuromas and failed to accurately depict their locations. MRN offered a comprehensive visualization of the entire nerve path, identifying nerve transection and neuromas, as well as precise location, dimensions, and relation to adjacent bones and muscles.

Conclusions: High-resolution 3-dimensional MRN provides clear visualization of acute and chronic peripheral nerve injuries of the head and neck region, facilitating early diagnosis of nerve injuries in this region and improving diagnostic accuracy, as well as surgical planning and execution. *(Plast Reconstr Surg Glob Open 2025; 13:e6475; doi: 10.1097/GOX.0000000000006475; Published online 27 January 2025.)*

INTRODUCTION

Peripheral nerve injuries (PNIs) of sensory nerves of the head and neck can occur as a result of trauma and/or iatrogenic injury during spine procedures, craniotomies and other interventions involving scalp incisions.[1,2] Following sensory PNI, painful neuromas may develop. This phenomenon occurs when an injured nerve starts to grow in an uncontrolled manner, resulting in a lump of unorganized axon fibers and nonneural tissue growth.[3]

Patients with acute PNI present with numbness in the nerve distribution and are often diagnosed with reversible nerve contusion (neuropraxia). However, if the numbness remains dense and does not begin to resolve in the first few weeks after injury, nerve transection should be considered and nerve imaging is warranted. If partial or complete nerve transection is missed, neuroma formation may occur.[4]

In chronic PNI cases, patients present with neuropathic pain in the distribution of the affected nerve, numbness, allodynia, cold intolerance, a positive Tinel sign, and pain drawings depicting nerve pain.[4,5] In addition, patients may experience different headache disorders, such as migraine, tension headache, occipital neuralgia, and trigeminal neuralgia.[6,7]

*From the *Department of Plastic and Reconstructive Surgery, Weill Cornell Medicine, New York, NY; †Department of Radiology and Imaging, Hospital for Special Surgery, New York, NY; ‡Department of Medical Imaging and Intervention, Chang Gung Memorial Hospital, Taoyuan, Taiwan; and §Department of Neurological Surgery, Weill Cornell Medicine, New York, NY.*

Received for publication August 6, 2024; accepted November 25, 2024.

Institutional review board registration: Weill Cornell Medicine: 23-04025985.

DOI: 10.1097/GOX.0000000000006475

Disclosure statements are at the end of this article, following the correspondence information.

Due to the complexity of diagnosing acute and chronic sensory nerve PNI, patients often experience extended periods of ineffective treatment, impacting quality of life and resulting in unnecessary healthcare expenses.[8,9]

Nerve imaging is an important diagnostic tool to further characterize PNI severity and differentiate PNI from other pathology such as chronic nerve compression, intracranial disorders, and spine pathology.[4] Furthermore, the confirmation of PNI through imaging can inform surgical decision-making and provide information to guide surgical planning.[10]

Although conventional magnetic resonance imaging (MRI) is able to identify nerve abnormalities with reported sensitivity and specificity ranging from 31% to 77% and 67% to 91%, MRI techniques in the head and neck are typically limited by vascular signal contamination, fat suppression inhomogeneity and suboptimal resolution that inhibit direct visualization of peripheral nerves.[11,12] magnetic resonance neurography (MRN) is an emerging technique that utilizes fat-suppressed, fluid-sensitive (ie, T2-weighted) sequences to create contrast between peripheral nerves and surrounding tissues and highlight nerve pathology.[13] On MRN, neuromas can be identified as peripheral nerves that are focally enlarged and lose their expected, internal fascicular architecture.[13,14]

Although MRN can assist in evaluating upper and lower extremity peripheral nerves, its use in the head and neck area is less explored, in part due to the frequently smaller caliber and tortuosity of extracranial nerves.[15–17] Nevertheless, MRN has been applied to diagnose greater occipital nerve (GON) neuropathy in patients with unilateral occipital pain, revealing increased GON diameter and signal intensity alterations.[18] Furthermore, MRN has also been used to image patients undergoing nerve decompression surgery of the GON to demonstrate the nerve's anatomical course and to delineate potential compression points suggested by focally thickened and hyperintense nerve segments.[19] However, there has been limited knowledge regarding the use of MRN for visualizing traumatic and iatrogenic PNI of the head and neck.

This article aimed to present the clinical features and diagnostic workup of patients with acute and chronic PNI of the head and neck using MRN, to demonstrate its capabilities in visualizing nerve injuries and to show potential advantages compared with conventional MRI examinations.

Takeaways

Question: Can magnetic resonance neurography (MRN) improve diagnosis and surgical planning for peripheral nerve injuries (PNIs) in the head and neck compared with conventional magnetic resonance imaging (MRI)?

Findings: This case series of patients with acute and chronic PNI demonstrates that high-resolution 3-dimensional MRN provides clear visualization of nerve transection and neuromas, accurately identifying their location and dimensions. MRN findings correlated well with intraoperative observations, whereas conventional MRI was less precise in depicting nerve pathology.

Meaning: MRN offers improved diagnostic capabilities for head and neck PNI compared with conventional MRI, potentially resulting in earlier diagnosis, more accurate surgical planning, and improved patient outcomes in cases of neuropathic pain.

METHODS

Institutional review board approval was obtained to retrospectively review the charts of 57 patients with headache disorders who presented to the senior author's headache surgery clinic from January to December 2023. Screening for PNI was performed by a peripheral nerve surgeon (L.G.) and included the following clinical criteria: previous trauma or surgery in the affected area, neuropathic pain in the nerve distribution with numbness and/or hypersensitivity, nerve pain on pain drawings, and pain relief following nerve blocks. If there was a clinical suspicion of traumatic or iatrogenic nerve injury, the patient was referred for MRN of the affected nerve(s). If a conventional MRI had already been conducted previously, the patients were not referred for MRN for insurance reasons and the existing images were used. All patients who underwent nerve exploration for suspected nerve transection or neuroma formation on imaging were included in this study. MRN and MRI findings were correlated with intraoperative observations.

MRN Technique

MRN was performed at 3-Tesla (GE Premier, GE Healthcare, Waukesha, WI) with a prototype, conformal 23-channel receive-only flexible array, which was shown to provide higher signal-to-noise ratio than conventional head and neck coils for imaging at higher spatial resolutions.[20] The protocol included a combination of T2-weighted, 2-dimensional fat-suppressed (Dixon) sequences in multiple planes (parameters: time-to-echo [TE] = 85 ms; repetition time (TR) = 3855 ms; echo train length = 16; acquired matrix = 320 × 288; field of view (FOV) = 12 × 12 cm; slice thickness = 3 mm; bandwidth = 244.1 Hz/pixel) and an 0.8-mm isotropic coronal or 0.7-mm isotropic oblique coronal 3-dimensional double echo steady-state sequence (TE = 5/9 ms; TR = 13.6 ms; acquired matrix = 256 × 256 or 288 × 288; FOV = 20.0 × 20.0 cm; bandwidth = 139.50 Hz/pixel, parallel imaging factors = 2 × 2). The double echo steady-state acquisition was reconstructed with a vendor-provided deep learning reconstruction algorithm (AIR Recon DL, GE HealthCare) for processing 3-dimensional (3D) data, to increase signal-to-noise ratio and edge sharpness.[21,22] A zero-echo-time (ZTE) sequence was also acquired to visualize bony landmarks (parameters: TE = 0 ms; TR = 545 ms; acquired matrix = 200 × 200; FOV = 18 cm; slice thickness = 0.9 mm; bandwidth = 651 Hz/pixel–1).

RESULTS

MRN Cases

Case 1

This 70-year-old man presented to our clinic with a diagnosis of chronic migraine confirmed by a neurologist.

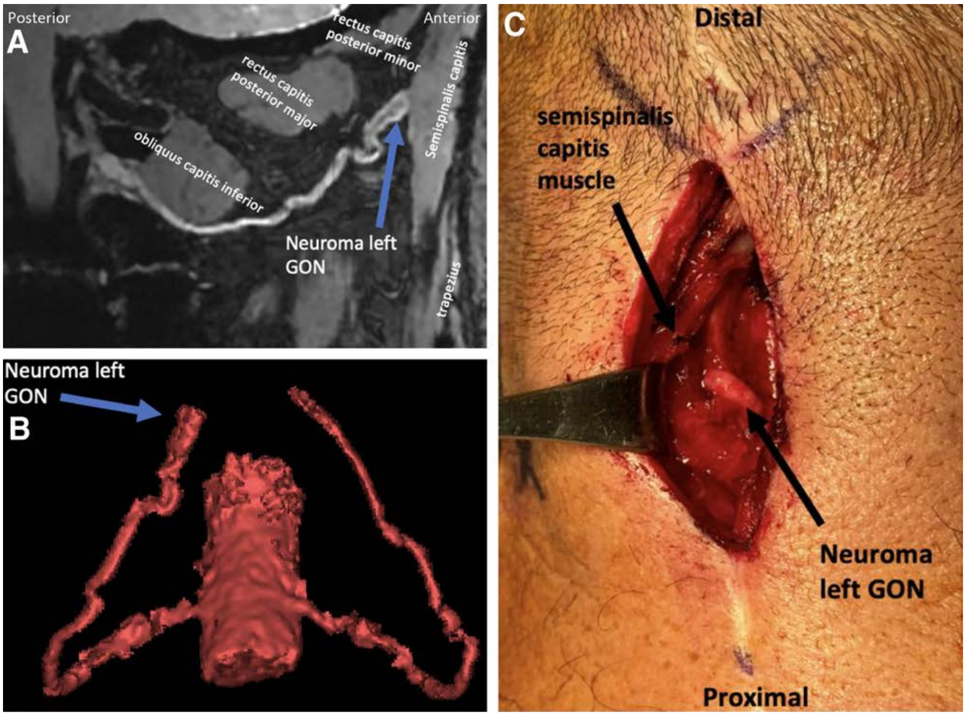

Fig. 1. Case 1. Fusiform neuroma of the left GON, shown on MRN (A and B) and intraoperatively (C).

He had a history of multiple cervical spine interventions. The patient reported continuous left occipital pain (10 on a visual analog scale of 0–10) and described the pain as sharp and stabbing, radiating from the back of the head to the forehead. He reported associated allodynia, intermittent numbness and migraines. Several migraine medications had failed, including abortive and preventative medications, as well as nerve medications, and the patient was currently being prescribed opioids. He further underwent several nerve blocks at the C1 and C2 levels that resolved his pain temporarily. Following a physical examination, he was referred for MRN. The images showed a 17-mm-long segment of the left GON that was markedly enlarged, as the nerve coursed deep to the semispinalis capitis muscle. The nerve abruptly terminated as a fusiform neuroma (Fig. 1). (**See Video 1 [online],** which displays case 1: the fused rendering of 3D MRN and ZTE imaging illustrates a neuroma of the left GON.)

Based on the MRN, the patient underwent surgical neuroma excision and nerve end reconstruction. Intraoperatively, the left GON was confirmed to be transected at the base of the semispinalis capitis muscle (Fig. 1). A fusiform neuroma was present at the stump and confirmed by pathology. The neuroma was excised until healthy fascicles were identified. Then, targeted muscle reinnervation (TMR) was performed between the GON stump and a semispinalis motor branch, and a vascularized regenerative peripheral nerve interface (RPNI) was wrapped around the coaptation site to avoid axonal escape (Fig. 2).[23] At 3-month follow-up, the patient reported complete relief of occipital nerve pain.

Case 2

A 39-year-old woman presented 1 week after a ski accident, which resulted in nasal bone fractures and a laceration of the left medial supraorbital rim that was sutured in the emergency department. The patient presented for suture removal and reported dense numbness and neuropathic pain along the left side of the forehead. Subsequent MRN showed enlargement of the left supratrochlear nerve (STN) as it exited the orbit and curved medially along the lateral margin of the left frontal sinus with suspected transection. The left supraorbital nerve (SON) had a normal appearance (Fig. 3). (**See Video 2 [online],** which displays case 2: the fused rendering of 3D MRN and ZTE imaging demonstrates the bilateral SONs, the bilateral STNs, and the bilateral frontal nerves, with suspected transection of the left STN.)

The patient underwent nerve exploration and repair 2 weeks after the initial injury. Intraoperatively, the SON appeared intact. The STN exited through a supraorbital notch and the nerve was found to split into 2 separate branches. Both nerve branches were transected. The medial branch had significant contusion and was retracted into the orbit. The lateral branch appeared healthier and was not retracted (Fig. 3). The nerve ends of the medial branch of the STN were debrided and reconstructed with a 1.5-cm, 1-2 mL nerve allograft. The lateral branch of the STN was directly coapted and repaired without tension. Ten weeks postoperatively, the patient reported return of sensation above her eyebrow and the proximal forehead. She described that she experiences nerve pain in this area which is decreasing in frequency and intensity.

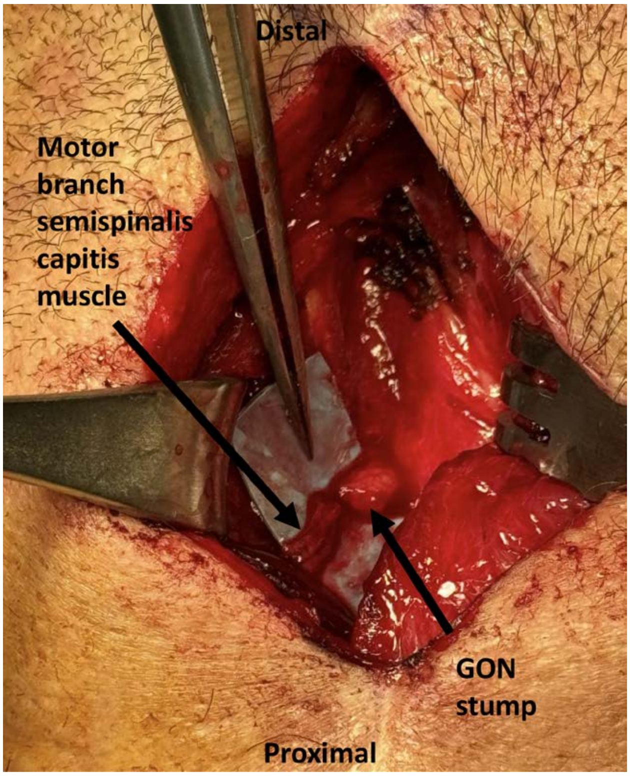

Fig. 2. Case 1. TMR was performed between the GON stump and a semispinalis motor branch. Photograph was taken before nerve coaptation.

MRI Cases

Case 3

A 38-year-old woman was diagnosed with occipital neuralgia and chronic migraines by a neurologist following a motor vehicle collision and whiplash 11 years ago. She underwent left GON decompression at an outside institution 8 years ago. Her symptoms improved temporarily but returned after several months. She then underwent neurectomy and nerve capping at an outside institution 3 years later. The pain completely resolved for 6 months and then returned. During screening in our clinic, she reported occipital pain with tenderness to palpation over the left GON and a positive Tinel sign. She underwent nerve blocks that relieved her pain for several hours. The patient had already undergone a neck MRI at an outside institution (Fig. 4). The radiology report outlined the presence of nodular enhancement, suggesting potential scarring or neuroma, of the left GON but no definitive diagnosis. Intraoperatively, the left GON was identified amidst scar tissue between trapezius fascia and semispinalis capitis muscle, where a large neuroma was identified (Fig. 4). Neurolysis of the GON was performed and the neuroma was excised. TMR and vascularized RPNI was performed by coapting the distal end of the GON to a semispinalis muscle motor branch and wrapping the construct with a semispinalis muscle cuff adjacent to the repair site (Fig. 5). At 12-month follow-up, the patient reported 80% improvement of occipital pain.

Case 4

A 34-year-old woman presented to clinic with chronic, daily headaches and occipital neuralgia. Her pain started after undergoing craniotomy, with hardware fixation, 3 years earlier. Her pain radiated from the left occipital region toward the left eye. She reported numbness in the left GON distribution and severe tenderness of the scalp, with accompanying allodynia. She underwent a neck MRI at an outside institution that was interpreted as a neuroma of the left GON between the semispinalis capitis and the splenius capitis muscle at the C2 level (Fig. 5). The patient was scheduled for hardware removal and/or replacement and resection/reconstruction of the GON

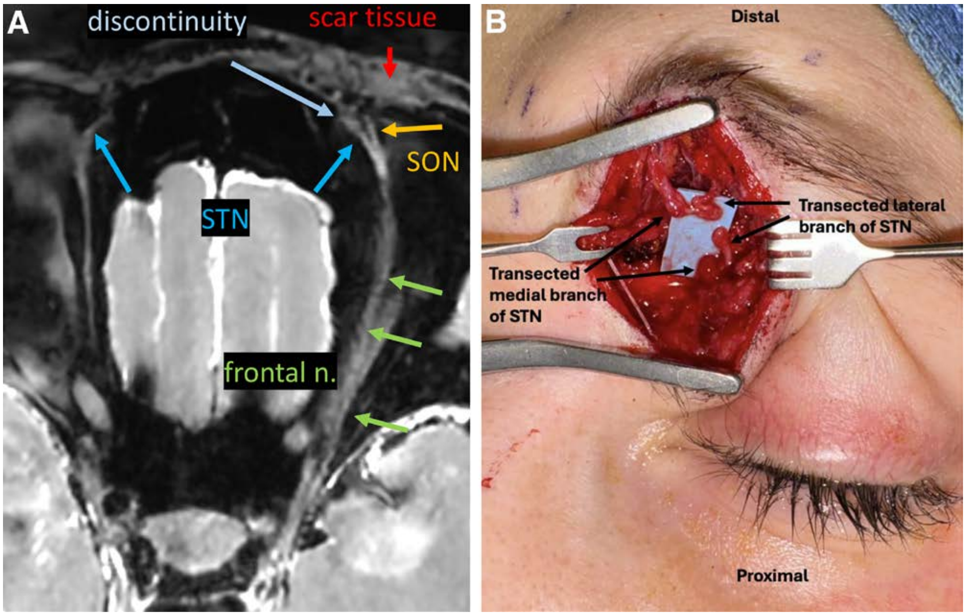

Fig. 3. Case 2. Enlargement of medial branch of left STN (purple arrow) with transection shown on MRN (A) and intraoperatively (B).

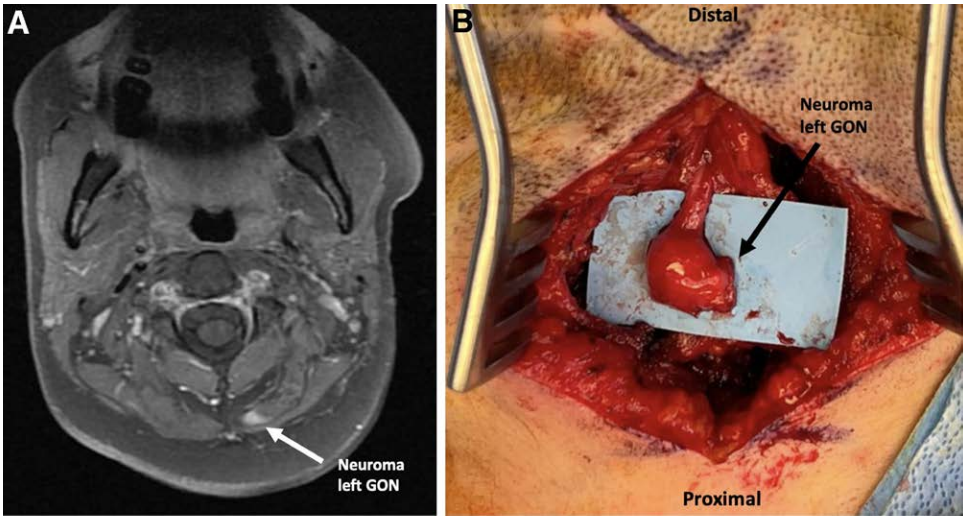

Fig. 4. Case 3. Neuroma of the left GON shown on MRI (A) and intraoperatively (B).

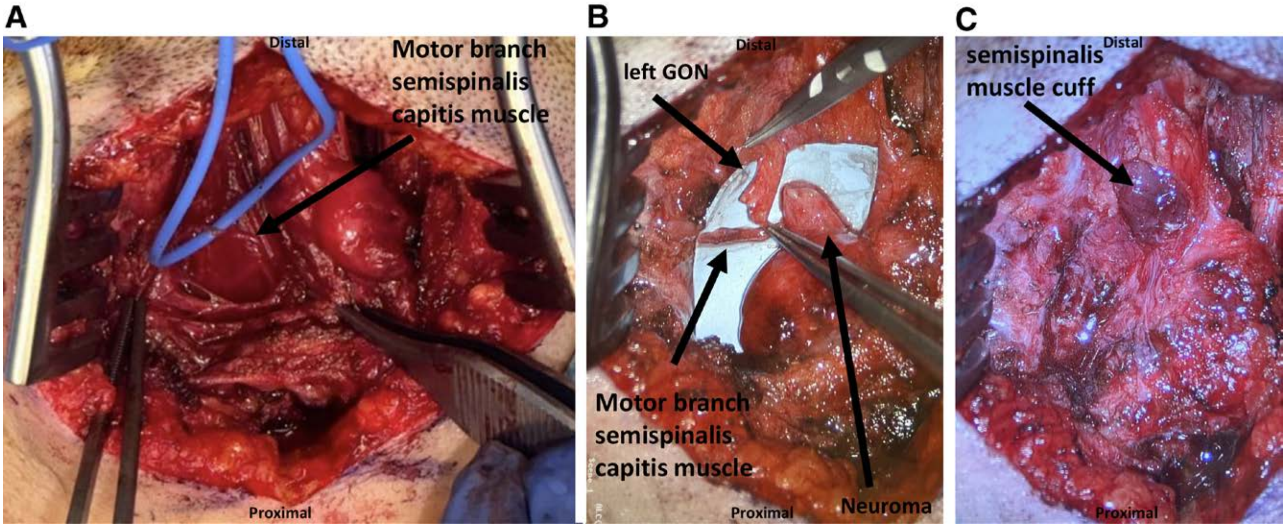

Fig. 5. Case 3. A, Identification of semispinalis capitis muscle motor branch (A). B, Coaptation of distal end of the left GON to the motor branch (TMR). C, Wrapping the construct with a semispinalis muscle cuff (RPNI).

neuroma. During surgery, hardware plates from prior surgery were removed and replaced with 2 plates away from the course of the GON. It was found that the GON was not in its typical anatomical location. The nerve was identified at the level of the prior plate, encased by scar tissue. Subsequently, extensive neurolysis was performed. The nerve was followed to its distal end, revealing a neuroma. The neuroma was found superficial to the hardware plates and was located at a more distal location than indicated on MRI. The neuroma was excised, and TMR with vascularized RPNI was performed by directly coapting the nerve end to a motor branch of the semispinalis capitis muscle. (**See Video 3 [online]**, which displays case 4: the intraoperative view of the left GON after neurolysis and neuroma excision.) Postoperatively, the MRI was again evaluated by a radiologist experienced in MRN and the presence of the neuroma at the site identified during surgery was confirmed (Fig. 6). At 12-month follow-up, the patient reported 85% improvement of symptoms in terms of frequency, duration, and pain intensity.

DISCUSSION

Advantages of MRN in Visualizing PNI

Patients with acute and chronic sensory PNI of the head and neck present with a wide variety of symptoms including neuropathic pain, numbness, allodynia, cold intolerance, and a positive Tinel sign, as well as different types of headache disorder. As a result, PNI symptoms are often misinterpreted, and patients are frequently misdiagnosed with migraine, headache, and trigeminal neuralgia. Conventional MRI can be used to detect PNI but may be limited by suboptimal spatial and contrast resolution.

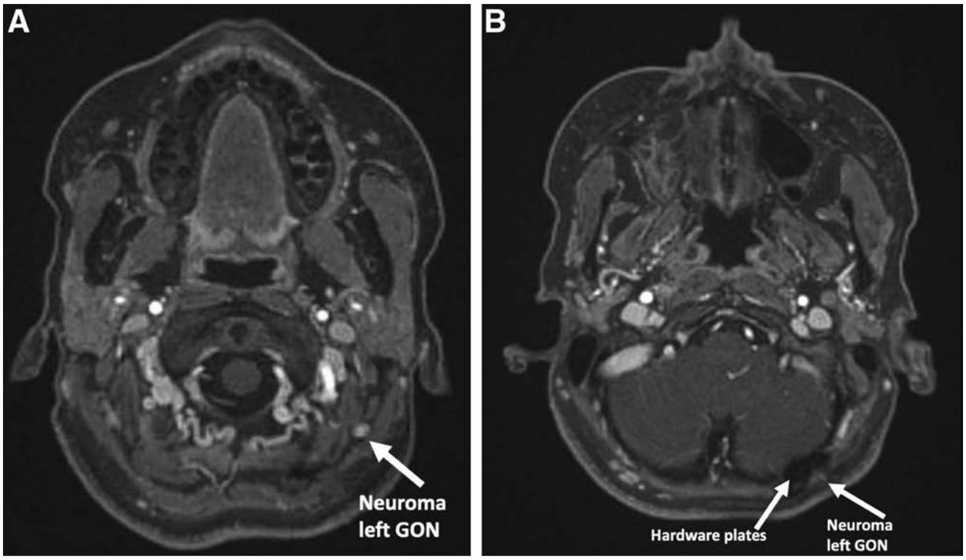

Fig. 6. Case 4. Identification of neuroma of the left GON during preoperative MRI assessment. A, The neuroma was identified between the semispinalis capitis and splenius capitis muscles at the C2 level. B, Postoperatively, the MRI was retrospectively reviewed by a radiologist experienced in MRN, confirming the presence of the neuroma superficial to the hardware.

Therefore, identification and confirmation of PNI of the head and neck is challenging and can lead to unnecessary treatment delays and patient morbidity.[8,9]

In this study, we show that MRN of the sensory nerves in the head and neck provides clear visualization of acute and chronic sensory PNI including nerve transection and neuroma. MRN was able to depict the entire nerve path and accurately identify both the location and dimensions of the injuries, which corresponded with the intraoperative findings. This indicates that the use of MRN in the diagnostic process of patients with suspected PNI may enable earlier and more accurate diagnosis and guide more targeted therapeutic interventions.

In acute cases, symptoms of sensory PNI, such as numbness, may be interpreted as neuropraxia, which typically recovers within weeks to months without intervention.[24] However, as demonstrated in this case series, dense numbness that does not improve in the first 2 weeks after injury warrants nerve imaging. Patients with missed injuries can develop permanent numbness and chronic neuropathic pain, which can be prevented by early nerve reconstruction surgery.[4] Therefore, timely diagnosis and confirmation of the degree of PNI are important to prevent neuroma formation and the associated clinical and economic burden of neuropathic pain.

Importance of Early Diagnosis and Intervention in PNI

It has been shown that neuropathic pain is extremely debilitating and is associated with substantially impaired health-related quality of life.[25] Patients describe that the pain impacts multiple health-related quality of life and functional domains, such as mobility, sleep, the ability to work, and participation in social events.[26] Furthermore, neuropathic pain is associated with substantial healthcare costs, including direct medical costs from treatments with nerve blocks and medications and indirect costs including inability to work and reduced work productivity.[8,9]

Moreover, patients who experience prolonged neuropathic pain may have a less favorable response to surgical interventions.[27] This response may be related to the development of central sensitization, which occurs when the patient's central nervous system is in a high activity state in response to persistent peripheral neuropathic pain. This high activity state not only increases pain perception in response to pain stimuli but also leads to pain in response to normal stimuli.[28] Consequently, even when the primary source of peripheral neuropathic pain is treated surgically, the persisting altered pain processing in the central nervous system may continue to generate and exacerbate pain symptoms, thereby diminishing the therapeutic efficacy of peripheral interventions.[29]

Integration of MRN Into Clinical Practice

To prevent the outlined negative consequences of neuropathic pain, integrating MRN into the diagnostic workflow for patients with suspected PNI is recommended. This approach facilitates improved diagnostic accuracy and surgical planning for patients with neuropathic pain of the head and neck. The use of MRN to detect PNI in the head and neck has been previously described by Chhabra et al.[30] The authors presented a case of a GON neuroma in a 46-year-old woman with chronic unilateral migraines. The MRN images showed a diffusely prominent GON with a focally thickened termination. In addition, 2 cases of iatrogenic PNI of the lingual nerve and the inferior alveolar nerve were described.[30] The authors concluded that more research is warranted to further evaluate the diagnostic accuracy of MRN in identifying PNI of the head and neck.

In a broader context, MRN has also demonstrated significant utility in assessing PNI in both upper and lower extremities.[31–33] It is being used as a valuable diagnostic tool to evaluate traumatic and iatrogenic nerve injuries, acute or chronic inflammatory conditions, neoplasms of the brachial plexus, and thoracic outlet syndrome.[34–38] Furthermore, MRN can be used to determine the exact location of upper and lower extremity nerve entrapment as well as evaluate nerve recovery following decompression surgery.[39] Furthermore, its ability to detect end bulb neuromas as well as neuromas in continuity in different nerves including the tibial nerve, medial antebrachial cutaneous nerve, and nerves within the brachial plexus highlights its diagnostic value. A neuroma in continuity typically manifests on MRN as a relatively well-circumcised, mass-like enlargement of the nerve, with preserved continuity of the nerve on either side. At the site of focal enlargement, loss of the expected fascicular architecture of the nerve can be appreciated on images orthogonal to the nerve's longitudinal axis. The degree of T2 signal intensity and contrast enhancement of neuromas may be variable.[40]

Comparison of MRN With Other Imaging Modalities

Although there is limited literature about the use of high-resolution ultrasound to assess PNI in the head and neck, it has been widely used in the upper and lower extremities.[17,41] Ultrasound allows for detailed real-time visualization of nerve and has demonstrated high sensitivity and specificity in diagnosing conditions such as entrapment neuropathies.[41] However, MRN provides a larger FOV which allows for visualization of the entire nerve path, superior soft tissue contrast, and improved visualizing of deeper structures that may be occluded by bony anatomy relevant in the head and neck regions. This may result in MRN having improved diagnostic capabilities as compared with ultrasound to assess complex nerve pathologies such as traumatic injuries and neuromas, where its ability to provide detailed tissue characterization is important.[42]

This case study suggests that MRN offers a comprehensive visualization of PNI compared with conventional MRI. However, it is important to note that no direct comparison between MRN and conventional MRI was performed in this study. Conventional MRI of the head and neck primarily uses 2D sequences. These images lack contiguous, high spatial resolution in all 3 dimensions, which is crucial for detailed visualization of the small and often tortuous peripheral nerves in the head and neck region. With technical improvements, 3D MRN has the capability to offer high spatial resolution (approximately 0.7–0.8 mm) in any arbitrary plane and can provide superior visualization of peripheral nerve anatomy.[43] The high spatial resolution is especially valuable for detecting and detailing morphological or signal intensity alterations associated with neuropathy or injury to small extracranial nerves. MRN scans can be complemented by the use of 3D ZTE sequences. These sequences can be used to generate computed tomography-like bone visualization, to delineate the spatial relationship of nerve injuries to osseous landmarks, which can be more readily identified by a surgeon.

CONCLUSIONS

This case series demonstrates the diagnostic capabilities of 3D MRN to visualize acute and chronic PNI of the head and neck. By enabling high-resolution, detailed imaging of nerve pathologies, MRN may facilitate improved diagnostic accuracy and surgical planning compared with conventional MRI.

Lisa Gfrerer, MD, PhD
Division of Plastic and Reconstructive Surgery
Weill Cornell Medicine
425 East 61st Street
New York, NY 10065
E-mail: lisa.gfrerer@gmail.com

DISCLOSURES

Dr. Sneag, Li, Dr. Tan, and Dr. Lin belong to the Hospital for Special Surgery that has institutional research agreements with GE HealthCare and Siemens. The other authors have no financial interest to declare in relation to the content of this article.

REFERENCES

1. Shaffrey EC, Seitz AJ, Albano NJ, et al. Expanding our role in headache management: a systematic review and algorithmic approach to surgical management of postcraniotomy headache. *Ann Plast Surg.* 2023;91:245–256.
2. Remy K, Hazewinkel MHJ, Mullen C, et al. Reoperation following primary greater occipital nerve decompression surgery: incidence, risk factors and outcomes [published online ahead of print April 9, 2024]. *Plast Reconstr Surg.*
3. Zabaglo M, Dreyer MA. Neuroma. In: *StatPearls.* StatPearls Publishing; 2023. Available at https://www.ncbi.nlm.nih.gov/books/NBK549838/. Accessed December 3, 2023.
4. Arnold DMJ, Wilkens SC, Coert JH, et al. Diagnostic criteria for symptomatic neuroma. *Ann Plast Surg.* 2019;82:420–427.
5. Gfrerer L, Hansdorfer MA, Ortiz R, et al. Patient pain sketches can predict surgical outcomes in trigger-site deactivation surgery for headaches. *Plast Reconstr Surg.* 2020;146:863–871.
6. Vorobeichik L, Fallucco MA, Hagan RR. Chronic daily headaches secondary to greater auricular and lesser occipital neuromas following endolymphatic shunt surgery. *BMJ Case Rep.* 2012;2012:bcr–2012-007189.
7. Gondo G, Watanabe T, Kawada J, et al. A case of cervicogenic headache caused by C5 nerve root derived schwannoma: case report. *Cephalalgia.* 2017;37:902–905.
8. Hazewinkel MHJ, Remy K, Knoedler L, et al. Treatment delay in patients undergoing headache surgery (nerve decompression surgery). *JPRAS Open.* 2023;38:226–236.
9. Hazewinkel MHJ, Remy K, Black G, et al. Treatment delay from onset of occipital neuralgia symptoms to treatment with nerve decompression surgery: a prospective cohort study. *Pain Med.* 2023;25:334–343.
10. Santiago FR, Muñoz PT, Pryest P, et al. Role of imaging methods in diagnosis and treatment of Morton's neuroma. *World J Radiol.* 2018;10:91–99.
11. Kwee RM, Chhabra A, Wang KC, et al. Accuracy of MRI in diagnosing peripheral nerve disease: a systematic review of the literature. *AJR Am J Roentgenol.* 2014;203:1303–1309.
12. Fisher S, Wadhwa V, Manthuruthil C, et al. Clinical impact of magnetic resonance neurography in patients with brachial plexus neuropathies. *Br J Radiol.* 2016;89:20160503.
13. Gasparotti R, Garozzo D, Ferraresi S. Radiographic assessment of adult brachial plexus injuries. In: *Practical Management of Pediatric and Adult Brachial Plexus Palsies.* 2012.

14. Chhabra A, Andreisek G, Soldatos T, et al. MR neurography: past, present, and future. *AJR Am J Roentgenol*. 2011;197:583–591.
15. Chhabra A, Williams EH, Wang KC, et al. MR neurography of neuromas related to nerve injury and entrapment with surgical correlation. *AJNR Am J Neuroradiol*. 2010;31:1363–1368.
16. Ku V, Cox C, Mikeska A, et al. Magnetic resonance neurography for evaluation of peripheral nerves. *J Brachial Plex Peripher Nerve Inj*. 2021;16:e17–e23.
17. Bink T, Hazewinkel MHJ, Hundepool CA, et al. Feasibility of ultrasound measurements of peripheral sensory nerves in head and neck area in healthy subjects. *Plast Reconstr Surg Glob Open*. 2023;11:e5343.
18. Hwang L, Dessouky R, Xi Y, et al. MR neurography of greater occipital nerve neuropathy: initial experience in patients with migraine. *AJNR Am J Neuroradiol*. 2017;38:2203–2209.
19. Salam K. Migraine surgery candidate selection with magnetic resonance imaging. American Society for Peripheral Nerve (ASPN), Nassau, Bahamas. 2023.
20. Abel F, Tan ET, Lunenburg M, et al. Flexible array coil for cervical and extraspinal (FACE) MRI at 3.0 Tesla. *Phys Med Biol*. 2023;68:215011–215068.
21. Lebel RM. Performance characterization of a novel deep learning-based MR image reconstruction pipeline. *Arxiv*. 2020.
22. Sun S, Tan ET, Mintz DN, et al. Evaluation of deep learning reconstructed high-resolution 3D lumbar spine MRI. *Eur Radiol*. 2022;32:6167–6177.
23. Gfrerer L, Wong FK, Hickle K, et al. RPNI, TMR, and reset neurectomy/relocation nerve grafting after nerve transection in headache surgery. *Plast Reconstr Surg Glob Open*. 2022;10:e4201.
24. Campbell WW. Evaluation and management of peripheral nerve injury. *Clin Neurophysiol*. 2008;119:1951–1965.
25. Hange N, Poudel S, Ozair S, et al. Managing chronic neuropathic pain: recent advances and new challenges. *Neurol Res Int*. 2022;2022:8336561.
26. Jensen MP, Chodroff MJ, Dworkin RH. The impact of neuropathic pain on health-related quality of life: review and implications. *Neurology*. 2007;68:1178–1182.
27. Hazewinkel MHJ, Remy K, Knoedler L, et al. Surgical treatment delay in patients with headache disorders and neuralgia correlates with poor postoperative outcome. *J Plast Reconstr Aesthet Surg*. 2024;99:154–159.
28. Dydyk AM, Givler A. Central pain syndrome. In: *StatPearls*. StatPearls Publishing; 2024. Available at https://www.ncbi.nlm.nih.gov/books/NBK553027/. Accessed May 16, 2024.
29. Woolf CJ. Central sensitization: implications for the diagnosis and treatment of pain. *Pain*. 2011;152:S2–S15.
30. Chhabra A, Bajaj G, Wadhwa V, et al. MR neurographic evaluation of facial and neck pain: normal and abnormal craniospinal nerves below the skull base. *Radiographics*. 2018;38:1498–1513.
31. Campbell GJ, Sneag DB, Queler SC, et al. Quantitative double echo steady state T2 mapping of upper extremity peripheral nerves and muscles. *Front Neurol*. 2024;15:1359033.
32. Davidson EJ, Tan ET, Pedrick EG, et al. Brachial plexus magnetic resonance neurography: technical challenges and solutions. *Invest Radiol*. 2023;58:14–27.
33. Lin Y, Tan ET, Campbell G, et al. Improved 3D DESS MR neurography of the lumbosacral plexus with deep learning and geometric image combination reconstruction. *Skeletal Radiol*. 2024;53:1529–1539.
34. Thejeel B, Tan ET, Colucci PG, et al. Early perioperative magnetic resonance findings in patients with foot drop following total hip arthroplasty: a descriptive case-series. *Eur J Radiol*. 2023;161:110727.
35. van Rosmalen MHJ, Goedee HS, van der Gijp A, et al. Quantitative assessment of brachial plexus MRI for the diagnosis of chronic inflammatory neuropathies. *J Neurol*. 2021;268:978–988.
36. Lin Y, Sneag DB. Thoracic outlet syndrome associated with a rib synostosis. *Radiology*. 2023;307:e223250.
37. Sneag DB, Rancy SK, Wolfe SW, et al. Brachial plexitis or neuritis? MRI features of lesion distribution in Parsonage–Turner syndrome. *Muscle Nerve*. 2018;58:359–366.
38. Upadhyaya V, Upadhyaya DN. Current status of magnetic resonance neurography in evaluating patients with brachial plexopathy. *Neurol India*. 2019;67:S118–S124.
39. Cudlip SA, Howe FA, Clifton A, et al. Magnetic resonance neurography studies of the median nerve before and after carpal tunnel decompression. *J Neurosurg*. 2002;96:1046–1051.
40. Ahlawat S, Belzberg AJ, Montgomery EA, et al. MRI features of peripheral traumatic neuromas. *Eur Radiol*. 2016;26:1204–1212.
41. Cartwright MS, Passmore LV, Yoon JS, et al. Cross-sectional area reference values for nerve ultrasonography. *Muscle Nerve*. 2008;37:566–571.
42. Parvathy G, Nazir A, Morani Z, et al. Unveiling the power of imaging techniques: comparing high-resolution ultrasound and functional MR neurography in peripheral nervous system pathology: a short communication. *Ann Med Surg (Lond)*. 2023;85:5834–5837.
43. van der Cruyssen F, Croonenborghs TM, Renton T, et al. Magnetic resonance neurography of the head and neck: state of the art, anatomy, pathology and future perspectives. *Br J Radiol*. 2021;94:20200798.