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Role of MR Neurography for Evaluation of the Lumbosacral Plexus: A Scoping Review

요천추 신경총에 대한 자기공명신경조영술의 역할: 주제 범위 문헌고찰

Seon Gyeong Kim, MD[1], Joon-Yong Jung, MD[2]*

[1]Department of Radiology, Yeouido St. Mary's Hospital, College of Medicine, The Catholic University of Korea, Seoul, Korea
[2]Department of Radiology, Seoul St. Mary's Hospital, College of Medicine, The Catholic University of Korea, Seoul, Korea

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***Corresponding author**
Joon-Yong Jung, MD
Department of Radiology, Seoul St. Mary's Hospital, College of Medicine, The Catholic University of Korea, 222 Banpo-daero, Seocho-gu, Seoul 06591, Korea.

Tel 82-2-2258-6254
Fax 82-2-599-6771
E-mail jy.jung@songeui.ac.kr

ORCID iDs
Seon Gyeong Kim https://orcid.org/0000-0002-5787-9154
Joon-Yong Jung https://orcid.org/0000-0002-6909-0919

Purpose MR neurography (MRN) is an imaging technique optimized to visualize the peripheral nerves. This review aimed to discover an optimized protocol for MRN of the lumbosacral plexus (LSP) and identify evidence for the clinical benefit of lumbosacral plexopathies.

Materials and Methods We performed a systematic search of the two medical databases until September 2021. 'Magnetic resonance imaging', 'lumbosacral plexus', 'neurologic disease', or equivalent terms were used to search the literature. We extracted information on indications, MRN protocols for LSP, and clinical efficacy from 55 studies among those searched.

Results MRN of the LSP is useful for displaying the distribution of peripheral nerve disease, guiding perineural injections, and assessing extraspinal causes of sciatica. Three-dimensional short-tau inversion recovery turbo spin-echo combined with vascular suppression is the mainstay of MRN.

Conclusion Future work on the MRN of LSP should be directed to technical maturation and clinical validation of efficacy.

Index terms Magnetic Resonance Imaging; Imaging, Three-Dimensional; Lumbosacral Plexus; Diffusion Tensor Imaging; Methods

INTRODUCTION

The lumbosacral plexus (LSP) is a group of nerve bundles interconnecting spinal nerve

roots and peripheral nerves of the lower extremities. Traditionally, lumbosacral plexopathy is mainly diagnosed based on neurologic exam, electromyography and nerve conduction studies (1, 2). However, the traditional approach has a limitation in locating the nerve abnormality precisely due to complex anatomy and inaccessibility to deeply seated peripheral nerves. Therefore, structural evaluation using imaging modality has been highly demanded.

MR neurography (MRN) is an imaging technique optimized to visualize peripheral nerves (3). Limitations in signal-to-noise ratio (SNR) and spatial resolution restrict clinical use at its earlier stage. However, with the wide use of high-field strength scanners and multichannel coil technology, MRN has become clinically more feasible. Particularly, isotropic three-dimensional (3D) images minimized the partial-volume averaging effect and enabled reformation of the nerve along its course (4, 5).

Although many qualified review papers regarding MRN were published in the recent decade, several questions were not clearly addressed. These include lack of a consensus on the sequences to be implemented in MRN for the LSP as well as determining which clinical situations the MRN benefitted patients with lumbosacral plexopathy. Therefore, a review on current status, and future direction of MRN for LSP is required. In this scoping review, the literature on MRN for the LSP was evaluated to suggest clinical indications, find optimal sequences, and to explore its potential benefits.

MATERIALS AND METHODS

Institutional Review Board approval was not needed because all data were reported in the literature. This scoping review was in compliance with the PRISMA Extension for Scoping Reviews (PRISMA-ScR) guidelines (6).

LITERATURE SEARCH STRATEGY

A search of the PubMed and Embase from January 1992 to September 2021 was performed

Table 1. Search Queries

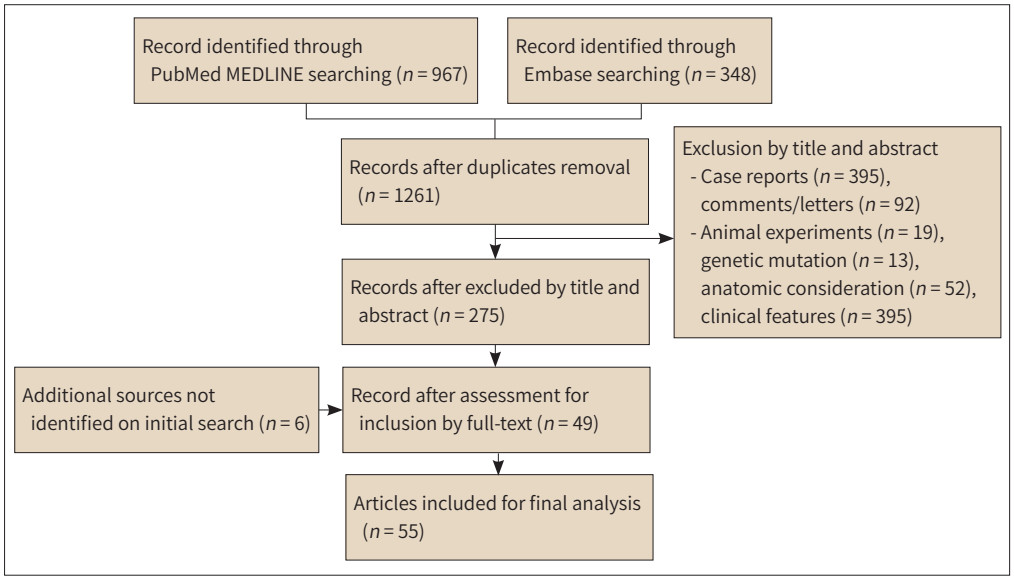
No.	Search Queries for MEDLINE
1	“Magnetic Resonance Imaging” [Mesh]
2	“Peripheral Nervous System Diseases” [Mesh] OR “Nerve compression syndromes” [Mesh] OR “Mononeuropathy” [Mesh] OR “Radiculopathy” [Mesh] OR “Neuralgia-sciatica” [Mesh] OR “Neuritis” [Mesh] OR “ Piriformis muscle syndrome” [Mesh]
3	“Lumbosacral Plexus (Femoral, Obturator, Pudendal, Sciatic Nerve)” [Mesh] OR “Ilioinguinal” OR “Iliohypogastric” OR “Femoral Cutaneous Nerve”
4	#1 AND #2 AND #3
5	#5 AND English[Lang] AND (“1992/01/01” [PDAT] : “2021/9/30” [PDAT])
No.	**Search Queries for Embase**
1	‘Lumbosacral plexus’/exp OR ‘lumbosacral plexus’
2	‘Nuclear magnetic resonance imaging’/exp OR ‘nuclear magnetic resonance imaging’
3	‘Neurologic disease’/exp OR ‘neurologic disease’
4	#1 AND #2 AND #3
5	#5 AND [english]/lim AND [1992-2021]/py

to identify articles focusing on MRN for LSP and its branches. To achieve this goal, we employed a strategy of search by combining three categories: modality, anatomy, and diseases (Table 1). MeSH terms and Emtree terms were used to search papers for MEDLINE and Embase, respectively. Peer-reviewed articles were included if they were written in English. In total, 967 papers from PubMed and 348 papers from Embase were found. After removing duplicates, titles and abstracts were reviewed to exclude comments, letters, and case reviews. Studies with animal subjects, or genetic mutation, experiment, anatomic consideration, and clinical features were also excluded. Finally, full-text articles were reviewed for final inclusion. The inclusion criteria were MR protocol specialized for nerve visualization, MR imaging of LSP or its branches, and assessment of clinical efficacy on neuropathies involving LSP or its branches. Six articles cited in the selected papers but not included in the initial search were additionally included because those contains core knowledge we sought for. Finally, 55 papers were included for our review (Fig. 1). Among the 55 papers, there were 30 original articles, 12 review articles, 9 technical notes, and 4 case series. One review article was a systematic review on diffusion tensor imaging (DTI) for compressed lumbosacral nerve roots (7).

QUALITY ASSESSMENT, KNOWLEDGE EXTRACTION AND CATEGORIZATION

The included original articles were independently reviewed by two readers based on the checklist for the assessment of methodological quality (Supplementary Table 1 in the online-only Data Supplement). Three subheadings were chosen to organize current knowledge on MRN for the LSP: indication, protocol, and supporting evidence from clinical studies. The MRN protocol was further divided into sub-categories: general consideration, sequences, vascular suppression, post-processing, contrast enhancement, and metallic-artifact reduction.

Fig. 1. Flow diagram of the article selection process.



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RESULT

INDICATION

The wide variety of LSP disorders, including infectious or inflammatory diseases, systemic diseases, and benign or malignant space-occupying lesions may present lumbosacral plexopathy, radiculopathy, or sciatica (8).

The pathologies of LSP can occur within or outside the spinal canal. The extraspinal causes include entrapment neuropathies, traumatic injuries, infection or inflammatory disease, primary or secondary tumor involvement, and vascular lesions. Timely detection and management of these lesions can be facilitated by MRN of LSP (9).

Preoperative MRN can be considered in patients with sciatica to confirm the course of sciatic nerves with respect to piriformis muscles and its asymmetry (10). MRN of the LSP may be significant in determining extraspinal causes of symptoms associated with failed back surgery syndrome (11).

Perineural injection is a promising treatment strategy for neuralgia among LSP branches. MRN can guide the perineural injection on individual nerve branches in the pre-procedural stage (12, 13). The pudendal and cluneal neuralgia are increasingly being recognized as a cause of chronic pelvic pain (12). MRI-guided perineural injection or cryoablation can also be considered for deeper nerve branches if MR-compatible equipment is available (14, 15).

Also, MRN is useful in demonstrating the distribution and characteristics of peripheral nerve diseases such as chronic inflammatory demyelinating polyneuropathy (CIDP), and hereditary motor and sensory neuropathy (Charcot-Marie-Tooth disease; CMT). Most CIDP and CMT show positive findings such as signal alteration and thickening in the MRN (16, 17).

MR PROTOCOL

GENERAL CONSIDERATION

3T scanners are better suited for MRN because it displays subtle morphological changes in small peripheral nerves because of the higher SNR and contrast-to-noise ratio (CNR). Fast spin-echo (FSE)-based 3D isotropic image acquisition allows multiplanar reformation along the course of peripheral nerves. Despite the long scan time of the 3D sequences, combination of fast imaging techniques such as parallel acquisition or compressed sensing can reduce the acquisition time to an affordable range (5, 18).

Dedicated high-resolution multichannel phased-array surface coils are essential to enhance the signal over a larger field-of-view (FOV) without sacrificing the SNR. For LSP imaging, the spine array coil and multi-channel body matrix coils are often combined in a wrap-around fashion (19).

Optimal FOV for LSP should include the lower lumbar spines, pelvis, and proximal thighs. Generally, coronal images centered at L5 with FOV of 300–320 mm covers the LSP from L1 root to pelvic floor where the pudendal nerves innervate (20, 21). However, lowering the center of FOV lower to S1–S2 root levels is more advantageous in evaluating the sciatic nerves (22). Including both sides in the FOV facilitates side-to-side comparison of nerve morphology and signal intensity. Increasing axial slice thickness up to 5–6 mm and placing a 2–4 mm interslice

gap while maintaining high in-plane resolution are acceptable strategies to achieve adequate coverage in a reasonable scan time (23). After screening a large area, imaging on a specific area of interest using a small FOV can be performed to obtain high-resolution MRN images (19). Oblique imaging centered on the sacrum could be better suited for sciatic and pudendal nerves visualization (24).

SEQUENCES

The routine sequences in the MRN protocol include 2D and isotropic 3D sequences with T1- and T2-weighted contrast. Axial T1-weighted images without fat suppression and fluid-sensitive T2-weighted images were obtained with high resolution (matrix size more than 256 in both directions) to depict the fascicular pattern of the nerves. Coronal T1-weighted and short tau inversion recovery (STIR), and proton density-weighted Spectral Attenuated Inversion Recovery (SPAIR) images show lesions along the long axis of the nerve and demonstrate other incidental findings in relation to the hips or spine (19). The echo time (TE) for 2D T2-weighted imaging is kept at 60 to 65 ms to achieve sufficient SNR and alleviate the magic angle artifact (5, 19).

3D FSE sequences are currently available on scanners from most vendors. For non–fat-suppressed 3D FSE T2-weighted imaging, the effective TE should be kept more than 90 ms to increase the contrast between normal and pathology in nerves. In contrast, effective TE should be lowered to 60 to 80 ms for fat-suppressed T2-weighted imaging to maintain SNR (19). However, appropriate TE should be optimized based on the voxel size and type of sequences. Magic angle effect should also be considered when the TE less than 60 ms is used (25). With an isotropic resolution of 1 to 1.5 mm, 3D sequences can be acquired in an acceptable range of times around 6 minutes (18, 24). The echo train length can vary from 3 to 8 for T1-weighted images, 8 to 22 for T2-weighted images, and 44 to 68 for 3D FSE sequences (19, 24).

3D gradient-echo (GRE) based steady-state sequences such as 3D balanced fast field-echo (bFFE) or constructive interference in steady-state (CISS) allow high-resolution imaging with excellent nerve to cerebrospinal fluid contrast when arachnoiditis, intrathecal infection, inflammation, or leptomeningeal metastasis are suspected (18, 26, 27).

Uniform fat suppression is critical in assessing the signal intensity of nerves. Frequency-selective fat suppression techniques are vulnerable to B0 and B1 inhomogeneity in large FOV imaging. STIR imaging offers robust fat suppression. However, TE should be lowered around 30–50 ms to maintain good SNR (23, 24). 3D FSE combined with STIR is a promising technique for LSP evaluation due to its high CNR between nerve and soft tissues and capability of multiplanar reconstruction. 3D STIR FSE depicts lesions along the long axis of the nerves and provides anatomic information that helps optimize preoperative planning (Fig. 2) (5).

Dixon-type fat suppression balances the need for homogeneous fat suppression and maintenance of SNR, and generally preferred if available (28).

Diffusion-weighted imaging (DWI) effectively improves nerve conspicuity by suppressing background tissues and vessels (29). In addition, DWI with DTI also provides quantitative values such as apparent diffusion coefficient (ADC) and fractional anisotropy (FA) (7, 30). For LSP, axial DTI is obtained with b-value of 600–900, and 15–20 directions (20, 31).

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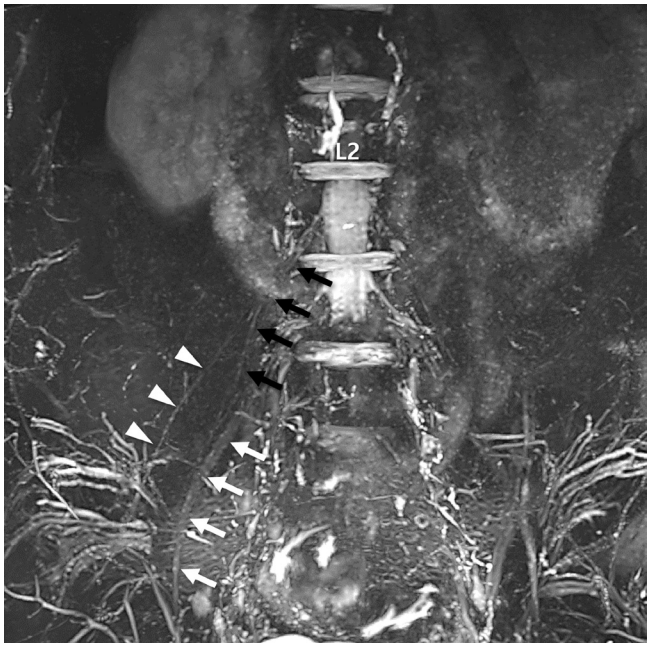


Fig. 2. Three dimensional short-tau inversion recovery fast-spin echo image with maximum intensity projection of the lumbosacral plexus. The courses of femoral nerve (white arrows), lateral femoral cutaneous nerve (arrowheads), and obturator nerve (black arrows) are well visualized. The femoral nerve (white arrows) is the largest branch of the lumbar plexus. It is derived from the anterior rami of nerve roots L2, L3, and L4. It travels inferiorly through the psoas major muscle. The femoral nerve then passes underneath the inguinal ligament to enter the femoral triangle. The lateral cutaneous nerve (arrowheads) arises from L2 and L3. It crosses the iliacus muscle obliquely, toward the anterior superior iliac spine. The obturator nerve (black arrows) receives from the anterior divisions of L2, L3, and L4. It longitudinally descends through the psoas major muscle fibers, and travels posteriorly to the common iliac arteries.

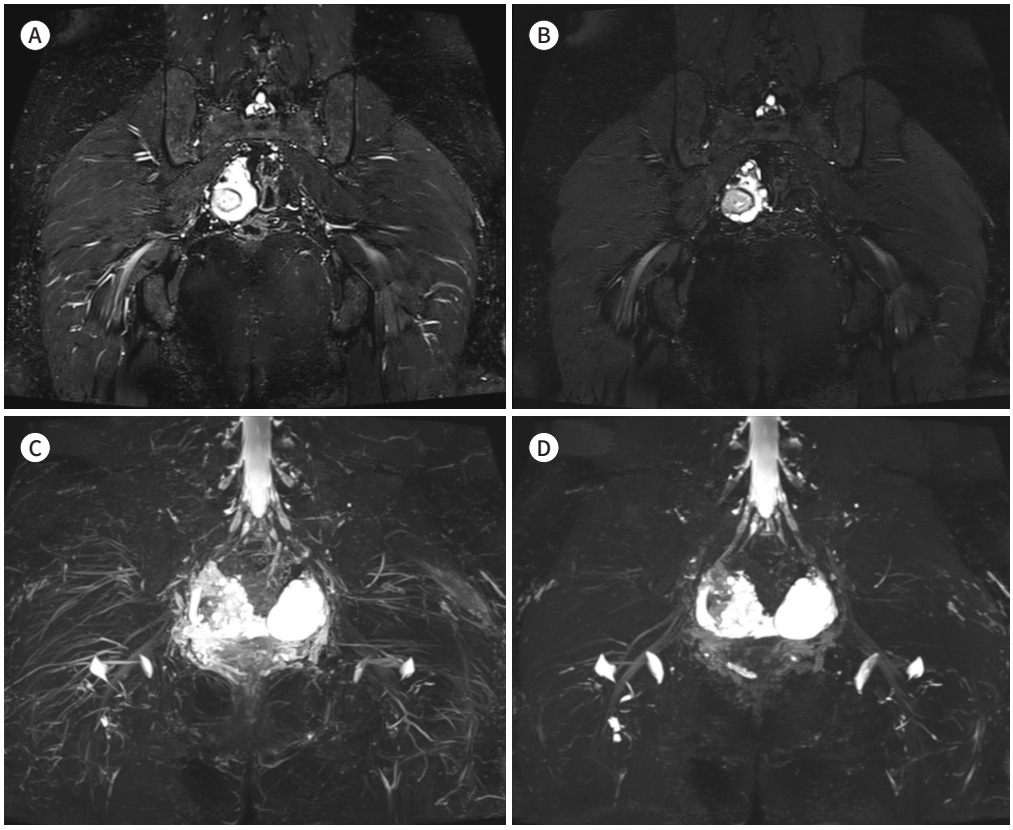
VASCULAR SUPPRESSION

Despite the sensitivity of fluid-sensitive sequences in visualizing nerves, hyperintense vascular structures accompanying nerves hinder a clear view of peripheral nerves. Recently, several techniques have shown potential in reducing hyperintense vessels and surrounding tissue in MRN (24, 32, 33). PSIF, so-called reversed fast imaging with steady-state precession (FISP), is a GRE sequence in which the dephasing of transverse magnetization drops the signal in flowing blood (34). The additional diffusion-gradient with a low b-value also suppresses the vascular flow signal by flow-related dephasing of the transverse magnetization (8, 19). However, this sequence is used to image peripheral nerves in extremities because of its vulnerability to local field inhomogeneity with a large FOV, and lack of additional benefit using diffusion-gradient.

3D nerve-sheath signal increased with inked rest-tissue rapid acquisition of relaxation imaging (SHINKEI) has been proposed to mitigate vessel-related signal contamination on peripheral nerves. This is a combination of spectral adiabatic inversion recovery pulse to suppress fat signal and an improved motion-sensitized driven-equilibrium pulse (iMSDE) before FSE sequence (18, 35). MSDE consists of motion sensitization gradients to suppress vascular flow and ensuing driven equilibrium pulse to eliminate the residual magnetization to enhance the nerve signal. Improved MSDE (iMSED) further enhances SNR by mitigating eddy current and local B1 field inhomogeneity (36). Patients with CIDP could be distinguished from healthy controls using simultaneous T2 mapping and neurography with SHINKEI in the lumbar plexus (37).

Recently, robust vascular suppression using STIR after gadolinium injection has been used. The signal intensity of enhanced blood is effectively suppressed by STIR because gadolinium has similar T1 relaxation time to fat (Fig. 3) (38). Post-gadolinium enhanced 3D FSE STIR provided higher nerve to vein CNRs compared to non-contrast images, resulting in increased conspicuity of LSP and its small branches (5, 38).

Fig. 3. Three dimensional short-tau inversion recovery fast-spin echo image (1-mm isotropic) before and after gadolinium injection (A, B), and corresponding maximal intensity projection of the sacral plexus of 2-cm-slab (C, D). Peripheral nerves appear more conspicuous after the vascular signal was suppressed by intravascular gadolinium.



POST-PROCESSING

Maximal intensity projection (MIP) with or without curved planar reconstructions from fat-suppressed 3D sequences allows excellent visualization of nerves and related pathologies. GRE type 3D imaging is less optimal for MIP due to low CNR between nerve and background tissue (18). Thinner slab MIP reconstructions does not show the full longitudinal course of the nerves, whereas thicker slab MIP results in a blurring of the nerves due to contamination of overlapping of vascular structures. In LSP imaging, 8-mm thick MIP is preferred when using 1.5 mm isotropic 3D STIR FSE (5, 19, 32). However, one study showed that 20-mm thick slabs provided the optimal longitudinal depiction of the nerves (18, 19, 39). The thickness and angulation for MIPs should be optimized according to the implemented sequences and nerves in particular interests (39).

CONTRAST ENHANCEMENT

The role of intravenous contrast in MRN is variably reported in the literature. Intravenous contrast may provide additional benefit in pathologic conditions, which may violate the integrity of the blood-nerve barrier. Such conditions include neural and perineural mass lesions, postoperative adhesion, radiation injury, inflammation, polyneuropathy conditions including lymphoma, amyloidosis, demyelinating neuropathies, and hereditary neuropathies (5, 19).

However, contrast-enhanced imaging does not add any value in trauma or entrapment neuropathy cases because most of the patients receive MRN in subacute stages where contrast-enhanced images will not change diagnostic interpretation of the neuropathy. There was no difference in nerve visualization and detection of nerve pathology between MRN with and without contrast-enhancement (40, 41).

METALLIC ARTIFACT REDUCTION

Metal artifacts degrade image quality and mimic abnormalities of peripheral nerves, in particular increased T2 signal on fat-suppressed T2-weighted images. 1.5T is preferred to 3T scanner for reducing metallic artifact if metal is present in the area of clinical concern. However, the optimal quality for nerve imaging at 3T outweighs the image degradation (42, 43). Conventional artifacts reduction strategies should be implemented by decreasing TE, increasing receiver bandwidth, placing frequency-encoding gradient along the axis of metallic instrument, using high resolution matrix and thin slice thickness. STIR is still the most viable option for effective fat suppression under the influence of metallic artifacts (42). Instead of GRE-based 3D sequences, FSE-based 3D sequence should be chosen. However, FSE sequences are still sensitive to the metal-induced artifacts in both readout- and slice-encoding directions (42, 43). Advanced multispectral techniques such as slice encoding for metal artifact correction (SEMAC) or multi-acquisition variable-resonance image combination (MAVRIC) have not been assessed yet in the context of MRN.

SUPPORTING EVIDENCE FROM CLINICAL STUDIES

There is a growing body of evidence that MRN of the LSP is useful to assess the radiculopathy of low extremities. Among 30 original articles, twenty-seven studies aimed to reveal the clinical impact of MRN on diseases involving LSP, and 7 of them was specifically focused on DTI.

MRN with the dedicated protocol for LSP showed significant correlation between abnormal intraneural T2 signal and active radiculopathy verified on EMG, although the positive MRN was not associated with subjective clinical symptom (44). Moreover, abbreviated MRN such as a single coronal STIR sequence added to routine spine MRI protocol discovered abnormalities which may have not been found with the spine MRI (45). In another study, MRN led the alterative diagnosis in 18 out of 23 patients with clinically suspected chronic cauda equina syndrome (46).

MRN of the LSP can also aid in revealing symptomatic nerve branches of LSP prior to perineural injection in patients with groin and genital pain (13, 47). Poh et al. (47) reported that 86% of patients who clinically suspected to have neuralgia of ilioinguinal, iliohypogastic or genitofemoral nerves, demonstrated abnormal signals. Interestingly, MRN revealed an alternative source of neuralgia involving the other cutaneous branches even in patients with negative MRN findings on the three nerves. In pudendal neuralgia, 90 of 139 showed pudendal nerve abnormality in MRN (13). More importantly, MRN demonstrated possible causes of neuralgia such as perineural scarring, Alcock's fascia thickening, mesh from previous surgery, edema or fat infiltration of obturator internus muscle in 42 patients (48). The presence of abnormal intraneural signals on MRN may identify the subset of patients who are likely to respond to targeted therapy. However, there were mixed results for the predicting response of

perineural injection in the MRN-positive group (48, 49).

MRN is helpful to assess demyelinating neuropathy of LSP. MRN of the LSP facilitated diagnosis of CIDP in patients who do not meet the electrodiagnostic criteria or present with atypical clinical features (50, 51). MRN of LSP was also proven useful in differentiating amyotrophic lateral sclerosis and multifocal motor neuropathy (52).

Traumatic injury of the LSP is relatively uncommon because LSP is less mobile than the brachial plexus, and protected by pelvic bone, spine and abdominal wall. Nevertheless, precise assessment on the severity of nerve injuries and timely referral for surgical intervention are paramount to expect the better surgical outcome. The overall sensitivity of 75% and specificity of 83% of MRN were reported to determine high grade LSP injury (53). In this context, MRN could also expedite the process by quickly evaluating the severity as compared to the electrodiagnostic tests in traumatic patients. The spontaneous recovery from post-traumatic LSP palsies could be predicted based on clinical and MR findings, although further validation is necessary in larger series (54).

DTI can provide additional information. FA reduction and ADC increase were the indicators of compressive neuropathy (7, 18) and diabetic amyotrophy (55). In a recently published systematic review, the authors found 10 papers regarding DTI on lumbosacral nerve roots (7). However, the selected papers in that review were DTI studies on lumbar spines mainly focused on spinal nerve roots and spinal nerves. Although several studies were performed on LSP and its branches (55-57), none of these demonstrated additional value to other MRN sequences.

DISCUSSION

The authors who originally coined 'MRN' described that the neurographic images analogous to angiography was available because peripheral nerves have longer T2 relaxation time than surrounding tissue (3). However, MRN was not generally accepted as a distinct technique until 3T MRI is distributed to the medical field. Plenty of articles were published for review or technical validation of MRN since dissemination of 3T MRI (5, 19, 27). These articles contributed to raise awareness on MRN and to establish MRN as a standard imaging technique. Nevertheless, studies which revealed clinical impacts of MRN were relatively scarce. Fortunately, a growing number of clinical studies are published, recently. These studies showed promising results that the MRN played an important role in diagnostic certainty and treatment decision-making (46, 47, 49, 51, 52). However, most of the studies were retrospective, and inevitably biased to positive side. Therefore, well-designed prospective study is necessary to provide unequivocal evidence for the use of MRN in clinical practice.

Placing large FOV is a major obstacle to obtain MRN of a good quality. LSP originates from L1 to S4 nerve roots and branches down to proximal thigh. Laterally, iliohypogastric and ilioinguinal nerves course over the psoas muscle and quadratus lumborum muscles passing through lateral abdominal wall (24). Therefore, it is not easy to include the entire LSP and its branches in one field. If possible, it is best to perform two different exams covering the entire course of the nerves. For example, the obturator nerve can be imaged with the combination of two exams, one MRN with centered on L3 and the other MRN of proximal thigh covering obturator foramen and innervating thigh muscles. In practical terms, small FOV imaging on a

specific area of interest is scanned after screening a large area with coronal 3D images (19). However, the recent development of the coil technology imparts more flexibility in prescribing FOV over a larger area by overlapping and molding coils (16, 27, 58).

The use of gadolinium in MRN is a controversial issue. Besides the potential hazard of intravenous gadolinium, contrast enhancement is still preferable in inflammatory or tumorous involvement of LSP (19). The use of gadolinium in MRN has an additional merit. Intravenous gadolinium with STIR can clearly visualize LSP by suppressing vascular signal (38). In a technical perspective, robust vascular suppression certainly has merit. However, it is still unclear whether the clearer MRN with solid suppression of vascular signal guarantee improved diagnostic performance and patients' outcome than that of suboptimal vascular suppression without contrast enhancement. Evidence-based practice guidelines should be developed on intravenous contrast use in MRN.

DTI on peripheral nerves is technically demanding although it is a well-established technique in the brain. DTI should be technically maturated to achieve high SNR and high resolution in an affordable scan time to be used in the clinical practice. In addition, more convincing evidence to support the use of DTI need to be built from quality studies A remarkable has been published which showed improvement of diagnostic accuracy in DTI-added MRN protocol compared to MRN without DTI in upper extremity (59). Well-designed studies like should be conducted to support the use of DTI as a part of routine MRN protocol of the LSP.

To summarize, there was significant knowledge gap on MRN in LSP imaging, despite the technical evolution of MRN over the last decade. Since LSP has complicated anatomic structure spanning a large area of body, implementation of MRN for LSP is still challenging. The literature review on MRN-LSP revealed that studies to support the clinical benefit of MRN were scarce currently. The direction of future works would be conducting the clinical studies to validate the clinical impact of MRN for the LSP and developing a practical guideline for implementation.

Supplementary Materials

The online-only Data Supplement is available with this article at http://doi.org/10.3348/jksr.2022.0001.

Author Contributions

Conceptualization, J.J.; formal analysis, all authors; investigation, all authors; methodology, J.J.; project administration, J.J.; resources, all authors; supervision, J.J.; visualization, all authors; writing—original draft, all authors; and writing—review & editing, J.J.

Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

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요천추 신경총에 대한 자기공명신경조영술의 역할: 주제 범위 문헌고찰

김선경[1] · 정준용[2]*

목적 자기공명신경조영술은 말초신경을 시각화하는 데 최적화된 영상 기법이다. 본 주제 범위 문 헌고찰에서는 요천추신경총에서 자기공명신경조영술의 프로토콜을 조사하고, 요추신경총 질환 환자에서 자기공명신경조영술의 임상적 이득에 대해 고찰하고자 한다.

대상과 방법 두 개의 의료 데이터베이스에서 2021년 9월까지 영문으로 출판된 논문에 대해 체계적 문헌검색을 수행하였다. ‘Magnetic resonance Imaging’, ‘lumbosacral plexus’, ‘neurologic disease’를 포함하는 55편의 논문을 분석하였다.

결과 요천추신경총의 자기공명신경조영술은 말초 신경 질환의 분포 확인, 신경 주변 주사시 유도, 좌골신경통 환자에서는 척추외 원인 평가에 유용하였다. 혈관억제 기법이 적용된 3차원 단시간 반전회복 고속 스핀에코 영상이 주된 자기공명신경조영술 기법이었다.

결론 향후 요천추신경총의 자기공명신경조영술에 대한 기술적 성숙과 임상적 유용성에 대한 검증이 필요하다.

[1]가톨릭대학교 의과대학 여의도성모병원 영상의학과,
[2]가톨릭대학교 의과대학 서울성모병원 영상의학과