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Possibilities of magnetic resonance imaging in visualizing the pudendal nerve in normal and pathological conditions

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Abstract

Until recently, imaging of peripheral nerves was limited from a technical point of view, as there was no established "gold standard" study protocol for the purpose of qualitative visualization of nerve trunks in normal and pathological conditions. With technical advances in magnetic resonance imaging and the advent of specialized high-resolution magnetic resonance neurography, it has become possible to visualize peripheral nerves of varying diameters. A literature search in the Pubmed, Medline, EMBASE, Cochrane Library, and eLibrary databases demonstrated the presence of several studies examining the capabilities of magnetic resonance imaging in visualizing the pudendal nerve in normal and pathological conditions. It must be emphasized that the results of these studies are consistent and largely complement each other. A generalization of the available data on the capabilities of magnetic resonance neurography of the pudendal nerve was the impetus for writing this literature review. Magnetic resonance neurography is a tissue-specific imaging method optimized for assessing the condition of peripheral nerves, including changes in the morphology of their bundle structure, signal, the diameter and length of nerve trunks, which can be caused by both anatomical features and pathological processes. Three-dimensional (3D) imaging is critical for studying the topography of peripheral nerves, identifying areas of compression or traumatic injury, and for preoperative planning. Magnetic resonance imaging in certain modes and sections allows to clearly visualize the pudendal nerve along almost its entire length, determine the nature of its branching and the features of its topographic and anatomical location. The anatomical characteristics of the pudendal nerve and its pathological changes obtained using magnetic resonance neurography can be used in everyday clinical practice by urologists, obstetricians-gynecologists and neurosurgeons for planning surgical interventions.

Keywords: pudendal nerve, pudendal nerve neuropathy, magnetic resonance imaging, magnetic resonance neurography, pelvic cavity.

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Background

Pudendal neuropathy is a distinct condition characterized by chronic neuropathic pain in the area innervated by the pudendal nerve and often accompanied by the sensation of a foreign body in the rectum/anus, urinary disorders, and sexual dysfunction [1]. The International Pudendal Neuropathy Association reports an incidence rate of 1/100,000 population per year for pudendal nerve neuropathy [2]. Spinosa et al. [3] found that the pudendal nerve neuropathy prevalence in the population is no more than 1%, with a higher incidence in women. In a study by Izvozchikov, the pudendal nerve neuropathy prevalence was 1.4% [4].

Pudendal nerve neuropathies are dramatic and difficult pathologic conditions to diagnose among all peripheral nervous system diseases [5]. Diagnosing pudendal nerve neuropathy can be challenging because of the referral process. Patients with chronic pelvic pain are often referred to neurologists and neurosurgeons by medical specialists, primarily urologists and gynecologists. However, establishing a clinical diagnosis of pudendal nerve neuropathy is rare in most cases [6].

Until recently, the visualization of peripheral nerves was limited by technical constraints owing to the absence of a "gold standard" protocol for high-quality visualization of nerve trunks in

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norm and pathology. However, technical advances in magnetic resonance imaging (MRI) and the development of specialized high-resolution MRI neurography enabled visualizing peripheral nerves of various diameters [7, 8].

A literature search in databases PubMed, Medline, EMBASE, Cochrane Library, and eLibrary revealed several studies on MRI of the pudendal nerve under normal and pathological conditions. The results of these studies are consistent and complementary in various respects. This literature review aimed to summarize existing data on the capabilities of magnetic resonance (MR) neurography of the pudendal nerve.

Technical features of magnetic resonance neurography

MR neurography is used for assessing the peripheral nerves. It can detect changes in bundle morphology, signal, nerve trunk diameter, and length, which may be due to anatomical features or pathological processes [9].

Three-dimensional (3D) imaging is crucial for studying the topography of peripheral nerves, identifying areas of compression or traumatic injury, and preoperative planning. MR neurography findings can be determined on T2-weighted and diffusion-weighted images. Diffusion-weighted MRI and diffusion-tensor MRI enable the evaluation of nerve trunk function. However, the use of diffusion-weighted and diffusion-tensor MRI in routine clinical practice is significantly limited because of special software requirements for this MRI mode and the extremely low signal-to-noise ratio (SNR) for small-diameter peripheral nerves [10, 11].

MRI machine magnetic field induction. Magnetic field induction affects both image quality and acquisition speed in MR neurography. Notably, 3 Tesla is more efficient than 1.5 Tesla [12]. The availability of high magnetic field induction neuroimaging has contributed to the development and integration of modern MR neurography into clinical practice [13].

Compared with 1.5 Tesla, 3 Tesla MRI machines provide a higher SNR ratio (almost twofold higher) owing to improved coil design, better gradient characteristics, and wider bandwidth. These advantages result in higher spatial resolution, thinner slices, improved fluid visibility, and significantly better anatomical characterization of nerve trunks and visualization of lesions [14].

Higher fluid contrast and more homogeneous fat-suppression techniques provide a better presentation of the fascial nerve structure. Additionally, MRI machines with high magnetic field induction exhibit a lower degree of magnetic field inhomogeneity [15]. MRI machines with high magnetic field induction have several advantages. They use multiple pulses of radiofrequency saturation to suppress signals from blood vessels effectively. Furthermore, they use parallel images to shorten the acquisition time.

However, obtaining high-quality T2-weighted images with 3D visualization on MRI machines with low magnetic induction is not feasible because of time and hardware limitations. Therefore, 3D gradient echo sequences should be used, which can result in non-isotropic images with low SNR, significant soft tissue contrast, and multiple artifacts. However, MRI machines with a magnetic field induction of 3 Tesla can easily produce high-quality isotropic 3D and T2-weighted images, which can serve as a valuable complement to two-dimensional images [16, 17].

Magnetic resonance research modes

High-resolution T1-weighted images are ideal for visualizing the normal anatomy of peripheral nerves and surrounding structures. Thin slices (maximum slice thickness: 4 mm) are adequate for defining anatomical details and bundle morphology. Large peripheral nerves are linear T1-hypointense structures with a clear anatomical distribution of fasciculi [18, 19].

Nerve trunks with larger diameters exhibit distinct differences from nearby blood vessels. Arteries appear as voids, whereas veins appear hyperintense on T1-weighted images. Importantly, the study of the fascicular anatomy of nerves is possible only when the diameter of the nerves is large and high-resolution MR tomograms are obtained.

A significant MRI semiotic sign of peripheral nerves is the presence of T1-hyperintense perineural fatty tissue with a characteristic pattern resembling “streetcar rails” appearing as alternating T1-hyperintense and T1-hypointense signals. Perineural fatty and soft tissue infiltration is adequately visualized on T1-weighted images. Moreover, T1-weighted images are the most sensitive in detecting fatty muscular dystrophy after innervation disruption [20, 21].

T2-weighted images. Pathological changes in the nerve trunks are most clearly visible on T2-weighted images. Additionally, volumetric masses and other pathological changes that typically result in nerve compression, such as cysts, peripheral nerve sheath tumors, and malignant peripheral nerve tumors, are best identified on T2-weighted images [22, 23].

Standard fast spin echo (without fat suppression) makes it difficult to distinguish abnormally elevated T2 signal from perineural and intraneural

fat on a T2-weighted image. Therefore, T2-weighted images with fat suppression are the optimal sequence for detecting nerve trunk lesions and are the most sensitive to early signal changes from muscles when their innervation is impaired [24]. However, T2-weighted fat-suppressed images are limited by more artifacts from hyperintense vascular structures and partial averaging of nerve fiber volume.

Vascular structures that accompany nerves can sometimes appear hyperintense, which may be mistaken for a nerve lesion or perineural edema [25].

Specialized MR neurography enhances the application of T2-weighted images with thinner slices to increase the contrast of image signal changes and achieve higher spatial resolution. The maximum contrast of T2-weighted imaging in nerves is achieved in three ways [26]: using sequences with long echo time (90–130 ms), using radiofrequency saturation pulses to suppress signals from nearby vessels, and using frequency-selective or adiabatic inversion recovery fat suppression imaging.

Enhanced T2-weighted images should be obtained at high magnetic field induction to ensure high-resolution neuroimaging. The critical role of technological advances in this process should be emphasized. This minimizes the possibility of false signals from vascular structures and adipose tissue and allows minimal signal changes from nerves. Novel methods, namely, stationary free precession and diffusion methods, are used in 3D imaging to suppress the vascular signal on T2-weighted images, particularly in limb imaging [27, 28].

3D visualization. Isotropic 3D imaging is crucial in modern MRI. Peripheral nerves are often oblique and difficult to see on standard axial, coronal, and sagittal slices. Further, 3D multiplanar reconstructed, curvilinear–planar reconstructed, and maximum intensity projection images are beneficial in visualizing the peripheral nerves. This is particularly critical for preoperative planning [29, 30].

Moreover, 3D imaging reduces artifacts and partial volume averaging, enabling a more accurate visualization of potential pathological processes in nerves. Moreover, changes in caliber and/or signal in nerve trunks, which may be imperceptible or associated with volume averaging on an axial slice, are better examined in the axial plane, allowing for a more precise assessment of the degree of abnormality. Certain nerve lesions, including plexiform neurofibromas, are particularly visible on 3D imaging [31].

Compression lesions of nerves caused by herniated discs, volumetric masses, and anatomical fibrous bone tunnels can be more accurately identified on 3D images. Three-dimensional reconstruction can be crucial in diagnosing and determining further surgical treatment tactics for a focal peripheral nerve interruption that is extremely difficult to identify on an axial slice. Furthermore, changes in muscle tissue volume and anatomy can be better assessed using 3D images [32].

Disadvantages of magnetic resonance neurography

"Magic angle" is observed in both tendon and peripheral nerve imaging. This phenomenon causes false signal enhancement when the nerve is positioned at a 55° angle relative to the main magnetic field vector. Although this effect can persist in nerves even at high echo times (>66 ms), it can be mitigated using longer echo times.

The radiologist should be vigilant when mentioning intraneural T2 signal enhancement in MR neurographic images in the study protocol because of the "magic angle" phenomenon. However, recent studies have shown that this phenomenon is a rare cause of false-positive interpretation in MR neurography, particularly for peripheral nerves that run parallel to the main magnetic field vector [33].

Although suppressive radiofrequency pulses are used, hyperintense vascular signals are often present in MR neurography, particularly at high echo time values. This can significantly complicate the radiologist's description of small-diameter nerve trunks when they are located near blood vessels, which may lead to misinterpretation of the obtained images.

MR neurography suffers from inhomogeneous fat suppression, particularly in the pelvis, because of the large field of view and presence of metal structures in the lower lumbar spine and/or hip joints. This further limits the local magnetic field, which worsens fat suppression [34].

To reduce hypersensitivity and chemical shift artifacts observed with 3 Tesla MRI, the echo time value should be reduced, parallel imaging should be performed, and the bandwidth should be increased. When evaluating nerves in close proximity to metal structures, 1.5 Tesla MRI machines may be more effective. Accurate absorption rate limits are reached more quickly at 3 Tesla than at 1.5 Tesla because of the increased energy for radiofrequency excitation. However, this difference is typically offset by faster image acquisition and shorter examination times, and it generally does not present challenges in clinical practice.

One potential disadvantage of 3D imaging is longer imaging times and time required to create and interpret multiplanar reformatted images [35].

Possibilities of magnetic resonance neurography of the pudendal nerve in normal individuals

MR neurography enables clear visualization of the pudendal nerve in various sections, including its

formation from the roots of the lumbosacral plexus, at the level of the sciatic ostium, in Alcock's canal, and in the male and female external genitalia. The right hemorrhoidal branch was visualized on MR tomograms of the male pelvis. However, other small branches of the pudendal nerve cannot be clearly seen [36, 37].

The pudendal nerve is most clearly visible on axial slices of T1- and T2-weighted images in the preliminary spectral saturation with inversion recovery (SPAIR) mode, which also enables the evaluation of its fascial structure. The proximal segment of the nerve can be identified along its axis on the oblique sagittal reconstruction of the 3D diffusion-weighted image. The pudendal nerve trunk can be seen on coronal slice T1-weighted images at the point where it enters Alcock's canal. T2-weighted images in 3D turbo spin-echo sequence mode are not appropriate for visualizing small branches of the pudendal nerve [38].

Possibilities of magnetic resonance neurography of the pudendal nerve in pathologies

Axial slices on T1- and T2-weighted SPAIR images should be analyzed in parallel to determine pathologic changes of the pudendal nerve. MR tomograms should be evaluated for signs of nerve trunk trauma or compression, scarring and adhesions along the nerve course, sacrococcygeal and/or sacrospinous ligament thickening, hind–limb fascia thickening, pubic and sacral bone deformation and/or fracture, and volumetric pelvic cavity masses [39].

The next step in describing MR tomograms of the pudendal nerve involves analyzing the signal intensity of the nerve and its branches. The roots of the lumbosacral plexus, which contribute to pudendal nerve formation, exhibit a bright hyperintense signal on T2-weighted images. Once the main nerve trunk is formed and the first-order branches are separated from it, the signal intensity reduces by almost half [8, 40].

The pudendal nerves can be most clearly seen on axial sections along the distal edge of the pectoralis muscle, where they enter the interosseous space at the sciatic ostium level. On T2-weighted images, the pudendal nerve in this anatomical region has a medium signal intensity and well-defined fascicular structure, making it easily distinguishable from blood vessels [41].

According to Filler, the presence of a hyperintense signal from the penile nerve or its rectal branch along the medial border of the internal constrictor muscle or proximal to its entrance into Alcock's canal is an indirect MRI sign of pudendal nerve neuropathy [42]. The authors suggest that minimal hyperintensity on T2-weighted images is common when the nerve enters Alcock's canal under the glenoid fascia, which may be related to the "magic angle" phenomenon [42]. The inferior rectal branch of the pudendal nerve can be challenging to visualize because of its oblique course in the sciatic–rectal tissue, accompanied by veins of the same name. In such cases, diffusion-tensor MRI is recommended to obtain a better definition of this branch.

The position of the inferior rectal branch in relation to the entrance of the pudendal nerve into Alcock's canal is unclear. One or more nerve trunks may be identified within this canal. Identification of the distal perineal branches can be challenging because of their small diameter and the presence of pelvic varices. A medium-intensity signal from the dorsal nerve of the clitoris or penis is identified just below the pubic symphysis on both sides in the area of the respective external genitalia. Three-dimensional imaging is crucial for evaluating the condition of major nerves in the lumbosacral plexus region [42].

The diagnosis of pathological conditions of the pudendal nerve requires examination of the sacral nerves and adjacent sternoclavicular muscle. Increased signal or size of the sacral nerves may indicate lumbosacral plexopathy (usually bilateral), trauma (e.g., bone fracture, trauma history, or adjacent muscle stretching), and perineural malignancy (nodular thickening and contrast enhancement) [43].

Traction neuropathy is a common type of pathology of the pudendal nerves. The main MRI characteristics include increased signal from the nerve and significant thickening due to perineural edema. This situation is often symmetrical.

Diffusion-tensor MRI can detect changes in nerve trunks by suppressing signals from surrounding fat, muscle, and vascular structures. T2-weighted imaging and diffusion-weighted MRI can make distal perineal and/or hemorrhoidal branches visible in the presence of pelvic scarring and adhesions. External genitalia inflammation or trauma can cause a hyperintense signal in the dorsal nerve of the penis or clitoris [44].

Data from MRI images should be carefully correlated with the clinical picture to determine the most appropriate therapeutic approach for each patient.

Conclusions

Thus, certain modes of MRI (T1- and T2-weighted images with 3D visualization) and slices allow clear visualization of the pudendal nerve along its entire length, enabling determination of its branching nature and topographic–anatomical location

features. The anatomometric characteristics of the pudendal nerve and signs of its pathological changes, as obtained by MR neurography, can be useful in the daily clinical practice of urologists, obstetricians–gynecologists, and neurosurgeons when planning surgical interventions.

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