Abstract

Purpose: Lumbosacral nerve root anomalies are relatively rare but can be a risk factor for intraoperative nerve injury. However, it is often difficult to evaluate them with preoperative imaging. We developed a software that automatically generates three-dimensional (3D) nerve root images from magnetic resonance (MR) imaging using artificial intelligence (AI). This study aims to evaluate the accuracy and utility of this modality in clinical practice by conducting an epidemiological study of nerve root anomalies.

Methods: The incidence and morphology of nerve root anomalies were evaluated in the 3D images of 1,500 patients. The accuracy of the images was evaluated by comparing the images generated automatically using this AI software with those created manually by conventional methods.

Results: Of 1,500 cases, 53 (3.5%) had nerve root anomalies with total of 58 nerve root anomalies. With respect to the spinal level, 35 nerve root anomalies were found in the L5-S1 level, the most common (60.3%). As for morphology, 47 nerve roots (81.0%) were of the Neidre–MacNab classification Type 1. The images matched in 1,493 out of 1,500 cases (99.5%) between the two methods, and the remaining 7 cases all had nerve root abnormalities, which were detected as abnormal by the AI software.

Conclusion: The MR nerve root 3D imaging provided a 3D visualization and understanding of nerve root morphology, including nerve root anomalies. The AI software enables easy and precise 3D nerve root imaging, which greatly aids in the preoperative evaluation for spinal surgery.

Keywords: artificial intelligence, lumbosacral nerve root, anomaly, epidemiology, 3D image

Introduction

Lumbar degenerative disorders, which cause lower back pain and leg pain, are among the most common spinal diseases. Surgical treatment is chosen when conservative therapy fails to improve the symptoms [1, 2]. While various surgical techniques and their effectiveness have been reported, iatrogenic nerve injury, one of the serious complications of the surgery, has remained an important issue to be discussed [3, 4]. One of the risks of intraoperative nerve injury is reported to be the presence of lumbosacral nerve root anomalies [5, 6]. In previous studies, the incidence of nerve root anomalies in the lumbosacral spine has been reported to vary from 0.49% to 30% [7, 8]. Although nerve root anomalies are not frequently present, it is essential to be aware of their presence during surgery because nerve root injuries can cause severe disabilities. In preoperative evaluation, nerve root anomalies are often diagnosed by magnetic resonance imaging (MRI) [3]. However, in the conventional two-dimensional (2D) MRI nerve root evaluation, it is often difficult to differentiate nerve root anomalies because, for example, a spinal canal stenosis lesion may cause the nerve root trajectory to meander or other abnormalities may be present [9, 10]. There is a risk of severe intraoperative nerve damage due to oversight with the conventional 2D MRI evaluation alone.

We focused on a technique for 3D imaging of the lumbosacral nerve that manually extracts nerve roots from MRI volume imaging data and creates a 3D image of the lumbosacral nerve using the volume rendering (VR) technique (Fig. 1). The 3D images created by this method easily allow for a 3D understanding of nerve course, making preoperative morphological evaluation simple and accurate. However, creating these images is manual, extremely complicated, and time-consuming (2–5 h per case), making it less versatile. Then we developed a software that automatically extracts 3D nerve images from MRI lumbosacral nerve volume data using artificial intelligence (AI) in collaboration with Fujifilm Co., Ltd. (Tokyo, Japan) [3]. This software is highly versatile and useful because it enables the acquisition of 3D nerve images with very simple operations in a short time (less than 10 s), facilitating the preoperative 3D understanding of nerve pathways and potentially reducing the risk of iatrogenic nerve injury [3].

Among the minimally invasive spine surgeries that have become increasingly popular in recent years, endoscopic spinal treatments, including fully endoscopic and microscopic or microscopic-endoscopic surgeries, are very minimally invasive [11, 12]. Full-endoscopic spine surgery includes transforaminal and interlaminar approaches and is highly useful with various techniques ranging from decompression and herniotomy to fusion [3, 4, 13-16]. However, there is a risk of injury to the exiting or traversing nerve root and dural mater during the surgical procedure. Since these are intraoperative complications that can occur during cannula placement and endoscopic insertion, it is imperative to check for any anomalies in the nerve root travel before surgery to prevent them. As with conventional surgical procedures, this is often due to a lack of preoperative recognition of nerve travel and morphology [5, 6, 16]. Therefore, the 3D nerve images generated by this software could be beneficial for preventing nerve injury in spine surgery, especially in endoscopic surgery.

This study aims to evaluate the accuracy of this imaging modality and its usefulness in clinical practice by conducting an epidemiological study on the incidence and morphology of lumbosacral nerve root anomalies on 3D images created using the newly developed software.

Materials and methods

Patients

Fifteen-hundred patients (642 males and 858 females; mean age ± standard deviation, 60.5 years ± 17.6 years) who underwent 3D lumbosacral nerve root MRI from April 2017 to September 2023 were included in this study. The diseases included 641 cases of lumbar canal stenosis, 453 cases of lumbar intervertebral disc herniation, 293 cases of lumbar degenerative spondylolisthesis, 44 cases of vertebral fracture, 31 cases of degenerative scoliosis, 30 cases of lumbar spondylolysis, and eight cases of tumor (Table 1). As for the participating patients, no inclusion or exclusion criteria were established. Institutional Review Board approval was obtained to conduct this study, and we obtained written informed consent from all subjects.

3D nerve root imaging created using AI

The method of creating 3D lumbosacral nerve root images using our software has been reported in a previous study [3]. An outline of the image creation method is as follows. A 1.5-T MRI system (Signa Creator; GE Healthcare, Chicago, IL) was used, and the imaging sequence was 3D multiple echo recombined gradient echo with fat suppression by water-selective excitation (field of view, 250 mm; thickness, 1.6 mm; time to repeat, 60 ms; echo time, Min Full; Flip angle, 13°). The images were created using SYNAPSE VINCENT, which automatically extracts 3D lumbosacral nerve root images using deep neural networks from volume imaging data containing lumbosacral nerves (Fig. 1).

3D nerve root imaging by conventional methods

The conventional manual method of creating a 3D nerve root MR image is as follows. The device and the imaging sequence were the same as the AI method. From the MRI volume image data, including the lumbosacral nerve, VR images of only the lumbosacral dural sac within the spinal canal were created manually. Then, VR images of the nerve roots originating from each lumbosacral dural sac were created by adding each to the dural sac.

Evaluation of images

The presence of nerve root anomalies was evaluated using the 3D lumbosacral nerve root MR images created using the AI method. For nerve root anomalies, the right and left sides of localization, the lumbosacral spine level of incidence, and the morphology using the Neidre–MacNab classification were evaluated [17]. Additionally, 3D nerve root images created using AI software were compared with those created by conventional manual methods in all 1,500 cases. The accuracy of nerve root delineation using AI software was evaluated based on those using traditional methods, and cases of nerve root imaging failure using AI software were extracted and evaluated. The AI software was used only for image construction, and the evaluation of nerve root anomalies was performed by the authors.

Results

The frequency of lumbosacral nerve root anomalies was 53 (3.5%) out of 1,500 cases. Regarding right and left localization, 33 (62.3%) were right-sided, 15 (28.3%) were left-sided, and five (9.4%) were bilateral, for a total of 58 nerve root anomalies (Table 2). With respect to the lumbosacral spine level, 35 nerve roots (60.3%) were located at the L5-S1 level, 19 (32.8%) at the S1-S2 level, and four (6.9%) at the L4-5 level (Table 2). As for morphological evaluation, 23 nerve roots (39.7%) were Neidre–MacNab classification Type 1a, 24 (41.4%) were Type 1b, one (1.7%) was Type 2b, and 10 (17.2%) were Type 3 (Table 2 and Fig. 2). Type 1, a conjoined nerve root, was the majority, with 47 nerve roots (81.0%) (Table 2 and Fig. 2).

A comparison of the 3D images between the AI and conventional methods in all 1,500 cases showed that the images matched in 1,493 out of 1,500 cases (99.5%). In all seven cases in which the images did not match, the 3D images using the AI method showed disrupted nerve root delineation, and the conventional method showed nerve root anomalies (Fig. 3). Five of the seven cases had Neidre–MacNab classification Type 3, one had Type 1a, and one had Type 1b. In all normally running cases without nerve root anomalies, the images were consistent between the two groups. Consistency was defined as no defect or excess in nerve root delineation by visual judgment.

Discussion

In this study, we investigated the epidemiology of nerve root anomalies in terms of incidence, spinal level of incidence, left-right localization, and morphological evaluation on 3D images of lumbosacral nerve roots created using AI technology-based software. Lumbosacral nerve root anomalies were first described by Zagnoni in 1941 [18], and Neidre et al. proposed the Neidre–Macnab classification, which classified nerve roots into Type 1 to

Type 3 based on their branching morphology in 1983 [17]. In previous studies, the incidence of nerve root anomalies in the lumbosacral region has been reported to be varied, with autopsy evaluations reporting relatively high values of 14% to 30% [8, 19]. In contrast, evaluations of intraoperative findings have reported lower values, with an incidence of 0.49% to 5.8% [7, 10, 20]. In addition, myelography evaluation has reported values of 2.2% to 4% [19, 21], and CT and MRI evaluation has reported various values ranging from 0.25% to 17.3% [9, 22-25]. The incidence of lumbosacral root anomalies detected by 3D MRI in this study was 53 out of 1,500 cases (3.5%), which is not significantly different from that in previous reports.

The large differences in incidence rates of nerve root anomalies, as described above, is presumably because of the limitations of imaging capability and the difficulty of image interpretation. In the first place, nerve roots are often meandering rather than straight, and the presence of compression factors or stenotic lesions adds to morphological changes such as flattening and changes in the course of the nerve root. Furthermore, the evaluation of images is often performed on CT or 2D MRI, making nerve root recognition very difficult [9, 22-25]. 3D nerve root MRI has been shown to be superior visually and easily help in understanding nerve root travel and morphology. Furthermore, the method of creating 3D MRI using AI demonstrated its usefulness in that the images can be created with simple operations. In actual clinical practice, it is possible to automatically acquire 3D images in a short time and with simple procedures after performing an imaging examination. These high-quality images are obtained with little time and effort on the part of the healthcare professional and the patient, resulting in good cost-effectiveness.

As for the spinal level at which the root anomalies are located, the highest incidence was at the L5/S level

(60.3%), similar to previous studies reporting that the L5/S level was the most common at 52–59% [10, 19, 21]. In terms of morphological evaluation, Manabe et al. reported that the most common anomaly is type 1, defined as a conjoined nerve root [22]. In this study, Neidre–MacNab classification Type 1 accounted for more than 80%, similar to that in previous reports [22]. On the other hand, although some studies have reported that left-sided localization is more common [22], in this study, 33 cases (62.3%) occurred on the right side, which is different from the previous study. However, there are few reports on the left and right localization of nerve root anomalies, and we concluded that further studies are needed in the future.

In this study, we compared 3D images created using AI technology with those created via conventional manual methods. However, there is an ongoing discussion about the appropriate metrics for deep learning segmentation. In this survey, we did not follow the most up-to-date recommendations such as Metrics Reloaded [26] and we recognize the need to consider them in the future. Furthermore, regarding the evaluation of image quality, another limitation is that we did not directly evaluate segmentation quality, such as computing Dice scores against a grand truth [27]. As a result, there were seven cases out of 1,500 cases in which the images did not match between the two groups, all of which had nerve root anomalies, and all of which were blank images in which the AI methods did not identify the anomaly site. Meanwhile, in 1,440 cases without nerve root anomalies, the images of the two groups were identical. It is expected that the ability to render these images will improve as the number of cases increases and deep learning is repeated. In summary, the images matched in 1,493 out of 1,500 cases (99.5%) between the two methods, and the AI software detected seven cases of nerve root abnormalities. These results suggest that the accuracy of the AI technology is very high compared to conventional methods as the comparative criteria. In contrast, focusing on nerve root anomalies, the poor accuracy cannot be denied, as 7 of the 53 cases with such anomalies could not be accurately delineated. Further refinement to this limitation must be considered in future studies.

Recently, while the application of minimally invasive spine surgery using endoscopes and other techniques has been widely reported, the incidence of nerve root injury in endoscopic herniotomy by the transforaminal approach has been reported to range from 1.0% to 6.7% [11, 12]. To prevent intraoperative nerve injuries, it is important to identify the nerve three-dimensionally before surgery, and this information can be used to consider modifying the approach route and surgical procedure. As minimally invasive surgery is currently required, 3D imaging will ensure safety. The software we have developed can automatically acquire 3D nerve images with a simple operation that takes only a few seconds, thus saving a great deal of time and effort required by conventional manual methods. This nerve root 3D rendering technology is innovative, useful, and convenient since safety can be easily obtained primarily in minimally invasive spine surgery. Furthermore, applying this technology to internal organs other than nerves facilitates 3D understanding of organs. It has already played an important support role, for example, by making it possible to understand the location of lesions in 3D during surgery [28, 29].

In this study, MRI was performed in the supine position, but most actual spine surgeries are performed in the prone position. Therefore, it is not certain that the 3D images obtained with this AI technology are identical to the condition of the nerves and surrounding tissues at the time of surgery. This is one of the limitations, and we will verify this in the future. Another limitation is that the survey was limited to the Japanese population. The results obtained in this study may be different for other ethnic groups, which should be expanded upon in future studies.

The other limitation is that only patients with some spinal disorders were included as examinees. This selection may be related to the incidence of nerve root anomalies and should be investigated in healthy controls in the future.

Conclusion

We evaluated anomalies of a lumbosacral nerve root in 3D nerve root MRI generated using AI technology. The incidence and morphology of nerve root anomalies were not significantly different from those reported previously. The accuracy of 3D nerve root delineation using AI software was 99.5% compared to the conventional methods as the comparative criteria. The remaining 0.5% of all cases were not delineated accurately, but the anomalies could be detected. Since a 3D understanding of the pathways of nerve roots is essential for spinal surgery, the newly developed software makes it possible to obtain 3D images with a simple operation, thus eliminating the effort and expense required for image creation in conventional manual methods, and is highly useful in preoperative evaluation of spine surgery. The simplicity and safety assurance made possible by this method will play an essential role in future spine surgeries.

Funding Declaration

This research did not receive any specific grant.

Ethics declarations

Ethical approval

All procedures performed in this study involving human participants were in accordance with the Declaration of Helsinki. Approval was obtained by the Institutional Ethics Committee of Sapporo Endoscopic Spine Surgery.

Informed consent

Informed consent was obtained from all participants in this study.

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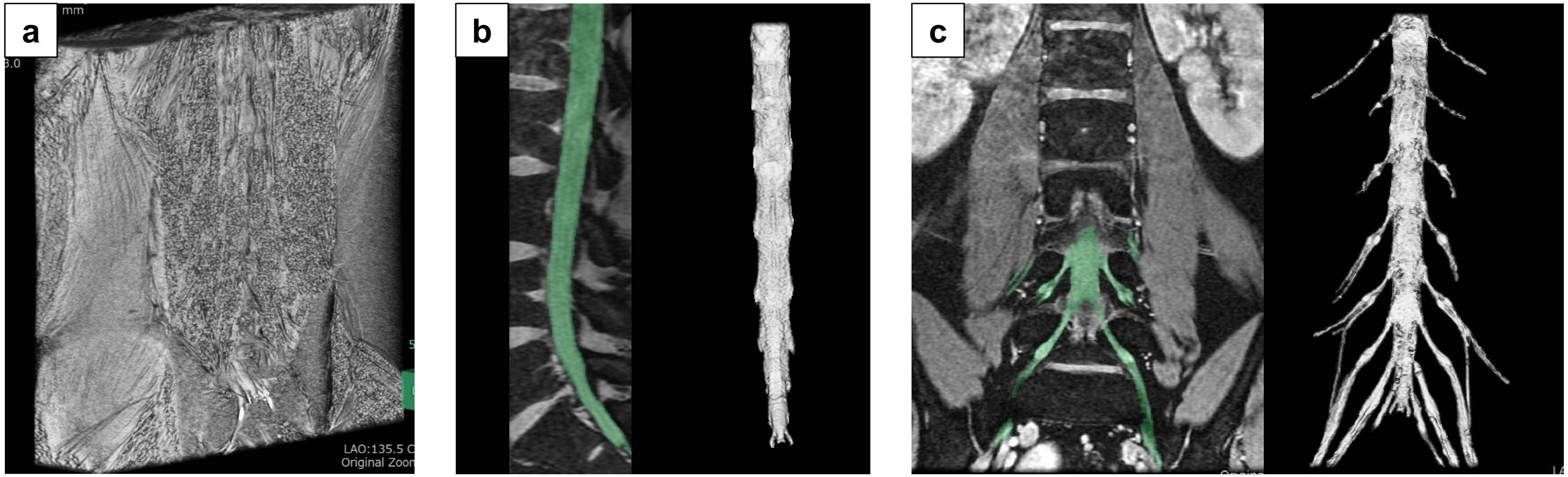
Figure captions

Fig. 1. Creation process of 3D lumbosacral nerve root MRI manually by conventional methods. (a) The MRI volume image data including the lumbosacral nerve, vertebra, and supporting tissue. (b) Extraction of lumbosacral dural sac within spinal canal from the MRI volume image data. (c) Adding each of the nerve roots to the dural sac. MRI, magnetic resonance imaging.

Fig. 2. Morphological evaluation of lumbosacral nerve root anomalies using the Neidre–MacNab classification. These are representative 3D nerve root images with abnormality created using artificial intelligence. The circles indicate nerve root anomalies. The Neidre–MacNab classification in each case is as follows; (a) Type 1a, (b) Type 1b, (c) Type 2b, (d) Type 3.

Fig. 3. The images of seven cases in which different images were rendered by artificial intelligence (AI) and conventional methods. In each case, the image with the AI method is shown on the left (gray) and the image with the conventional method on the right (yellow). The area circled in red is the point of difference, where the description of the nerve is deficient. The Neidre–MacNab classification in each case is as follows; (a) Type 1a, (b) Type 1b, (c-g) Type 3.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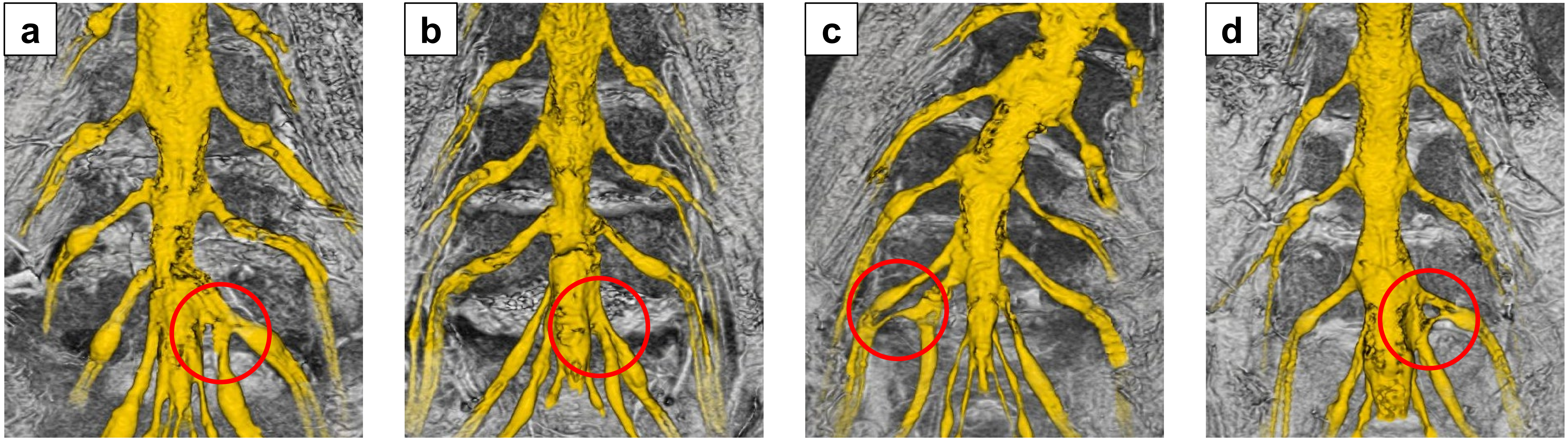
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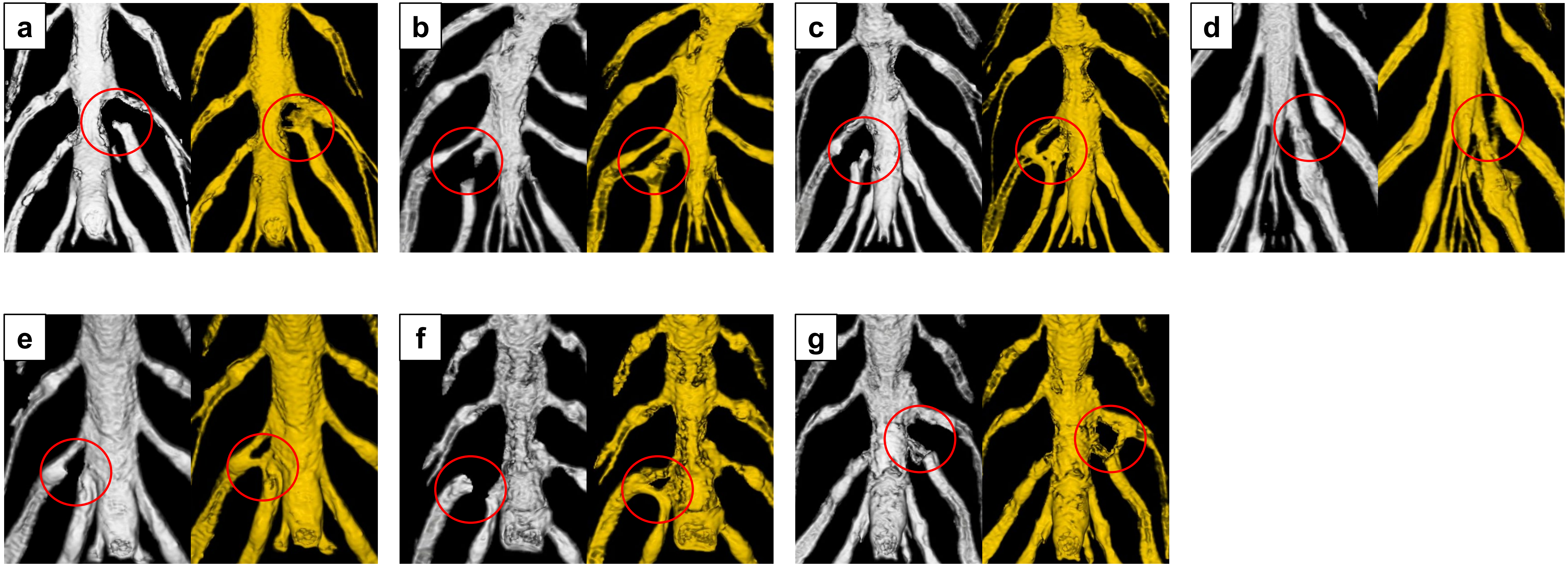
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Tables 1. Patient characteristics (N = 1,500)

	N = 1,500
Mean age, years (range)	60.5 (11-92)
Men / Women	642 / 858
Diagnosis	
Lumbar canal stenosis	641
Lumbar intervertebral disc herniation	453
Lumbar degenerative spondylolisthesis	293
Vertebral fracture	44
Degenerative scoliosis	31
Lumbar spondylolysis	30
Tumor	8

Tables 2. Summary of localization and morphology of nerve root anomalies (53 cases, 58 nerve root)

	53 cases, 58 nerve root
Left	15 (28.3%)
Right	33 (62.3%)
Bilateral	5 (9.4%)
Level	
L4/5	4 (6.9%)
L5/S1	35 (60.3%)
S1/2	19 (32.8%)
Neidre-MacNab classification	
Type 1a	23 (39.7%)
Type 1b	24 (41.4%)
Type 2a	0 (0%)
Type 2b	1 (1.7%)
Type 3	10 (17.2%)