Received:
12 December 2016

Revised:
08 August 2017

Accepted:
31 August 2017

<https://doi.org/10.1259/bjr.20160929>

Cite this article as:

Kanamoto H, Eguchi Y, Oikawa Y, Orita S, Inage K, Fujimoto K, et al. Visualization of lumbar nerves using reduced field of view diffusion tensor imaging in healthy volunteers and patients with degenerative lumbar disorders. *Br J Radiol* 2017; **90**: 20160929.

FULL PAPER

Visualization of lumbar nerves using reduced field of view diffusion tensor imaging in healthy volunteers and patients with degenerative lumbar disorders

¹HIROHITO KANAMOTO, MD, PhD, ²YAWARA EGUCHI, MD, PhD, ³YASUHIRO OIKAWA, MD, PhD,
¹SUMIHISA ORITA, MD, PhD, ¹KAZUhide INAGE, MD, PhD, ¹KAZUKI FUJIMOTO, MD, PhD, ¹YASUHIRO SHIGA, MD, PhD,
¹KOKI ABE, MD, ¹MASAHITO INOUE, MD, ¹HIDEYUKI KINOSHITA, MD, ⁴KOJI MATSUMOTO, MD,
⁴YOSHITADA MASUDA, PhD, ¹TAKEO FURUYA, MD, PhD, ¹MASAO KODA, MD, PhD, ⁵YASUCHIKA AOKI, MD, PhD,
⁵ATSUYA WATANABE, MD, PhD, ¹KAZUHISA TAKAHASHI, MD, PhD and ¹SEIJI OHTORI, MD, PhD

¹Department of Orthopaedic Surgery, Graduate School of Medicine, Chiba University, Inohana, Chuo-ku, Chiba, Japan

²Department of Orthopaedic Surgery, Shimoshizu National Hospital Shikawatashi, Yotsukaido, Chiba, Japan

³Division of Orthopaedic Surgery, Chiba Children's Hospital, Heta-Chou, Midori-ku, Chiba, Japan

⁴Department of Radiology, Chiba University Hospital, Inohana, Chuo-ku, Chiba, Japan

⁵Department of Orthopaedic Surgery, Eastern Chiba Medical Center Okayamadai, Togane, Chiba, Japan

Address correspondence to: Dr Yawara Eguchi

E-mail: yawara_eguchi@yahoo.co.jp

Hirohito Kanamoto and Yawara Eguchi have contributed equally to this work.

Objective: We investigated high resolution diffusion tensor imaging (DTI) of lumbar nerves with reduced field of view (rFOV) using 3 T MRI.

Methods: DTI measured with rFOV was compared with conventional FOV (cFOV) 3.0 T MRI in 5 healthy volunteers and 10 patients with degenerative lumbar disorders. The intracanal, foramina and extraforamina of the L5 nerve were established as the regions of interest and fractional anisotropy (FA) values and apparent diffusion coefficient (ADC) values were measured. Image quality for tractography and FA maps and ADC maps, interindividual and intraindividual reliability of FA and ADC, and signal-to-noise (SNR) were studied.

Results: Both of image qualities with tractography, FA map and ADC map showed that lumbar nerves were more clearly imaged with the rFOV. Intraindividual reliability was higher with rFOV compared with the conventional method for ADC values, while interindividual reliability was higher for both FA values and ADC values with the rFOV method over the conventional method ($p < 0.05$). Significantly higher SNR was

obtained with rFOV compared with cFOV in the spinal canal ($p < 0.05$).

Conclusion: rFOV enabled clearer imaging of the lumbar nerve, allowing for more accurate measurement of FA and ADC values. Significantly higher SNR was obtained with rFOV compared with cFOV in the spinal canal. To our knowledge, this research showed for the first time the usefulness of rFOV in patients with degenerative lumbar disorders. High resolution DTI using rFOV may become useful in clinical applications because visualization of nerve entrapments and quantification of DTI parameters may allow more accurate diagnoses of lumbar nerve dysfunction.

Advances in knowledge: Compared with traditional methods, rFOV allows for clear imaging of the lumbar nerve and enables accurate measurements of the FA and ADC values.

High-resolution DTI with rFOV may be used to visualize nerve entrapments and allow for more accurate diagnosis of DTI parameter quantification with opportunities for clinical applications.

INTRODUCTION

Diffusion weighted imaging (DWI) based on MRI yields useful information regarding tissue microstructure because it monitors the random movement of water molecules, which is restricted by applying a motion probing gradient

(MPG) in some directions.^{1–4} DWI data can be used to determine quantitative values, such as the apparent diffusion coefficient (ADC). DWI is essential in the diagnosis of acute phase cerebrovascular infarction,⁵ and it is currently widely used in clinical practice.^{6,7} DWI has a strong effect

not only on the ease but also the directionality of water molecule dispersion. In nerve fibres, axonal cell membrane and myelinated sheaths prevent dispersion in the direction directly aligned to the nerve fibre bundle, resulting in the loss of water molecule isotropy. This condition is referred to as anisotropy and diffusion tensor imaging (DTI) and tractography are examples of selective recording of this data. A parameter of anisotropic strength is fractional anisotropy (FA) which is expressed in values from 0 to 1. The closer the value is to 1, the stronger the anisotropy, while a value of 0 is complete isotropy. More recently, DTI has been reported useful in demyelinating diseases such as multiple sclerosis or chronic peripheral nerve compression lesions such as carpal tunnel syndrome.^{8,9} Water molecule dispersion because of myelin sheaths in myelinated nerves in tissues is limited to directions parallel to the nerve fibres revealing high anisotropy features, but when demyelination occurs as a result of nerve injuries such as spinal cord injury, the anisotropy decreases leading to decreases in FA values.^{10,11}

Lumbar nerve DTI has been reported as useful for diagnosis of foraminal stenosis. Thus far, we have seen a disruption of the tract in lumbar foraminal stenosis with DTI, and that FA values are decreased.¹²

However, because DTI requires a high magnetic field, the magnetic susceptibility effect and increases in motion artefacts lead to signal irregularities and image distortion so that nerve fibre follow-up would be limited in areas with artefacts. In the future, further improvements in image resolution are essential for clinical applications. The loss of signal inherent to smaller voxels needs to be counterbalanced by a higher signal-to-noise ratio (SNR), which is necessary to obtain accurate measurements of DTI parameters.

A new reduced field of view (rFOV) single-shot diffusion-weighted echoplanar imaging method is proposed, in which a 2D spatially selective echoplanar RF excitation pulse and a 180° refocusing pulse reduce the FOV in the phase-encode (PE) direction, while simultaneously suppressing the signal from fat. The rFOV methods decrease the required readout duration and allow the acquisition of high-resolution diffusion-weighted images, enabling its practical application to imaging of the spine.¹³

There are varied reports of the use of DTI with rFOV in cerebral nerves and in the region of the cervical vertebrae,^{14–16} but to our knowledge only one article has reported on its use in the lumbar region.¹⁷ The purpose was to investigate high-resolution DTI of lumbar nerves with rFOV compared with conventional FOV (cFOV) using 3 T MRI.

METHODS AND MATERIALS

Participants

All subjects provided written, informed consent before taking part in the research, which was approved by the institutional review board.

We studied 5 healthy normal volunteers (4 males; mean age: 27.2 years) and 10 patients with degenerative lumbar disorders

(5 males; mean age: 59.2 years). Patients with a history of spinal trauma, surgery, neurological disease, or contraindication for MRI were excluded. Seven patients with lumbar spinal stenosis (LSS) and three with lumbar disc herniation were investigated in the present study.

Conventional MRI

The patients were studied using a 3.0 T MR system (Discovery MR 750, GE Healthcare, Waukesha, WI). Conventional MRI scans consisted of T_1 weighted (T1W) and T_2 weighted (T2W) sagittal images, and T_2 weighted axial images were also obtained. For sagittal imaging, the acquisition settings were as follows: FOV = 260 × 260 mm, slice thickness = 3 mm echo time (TE)/time of repetition (TR) = 8.4/530 ms (T1W) and TE/TR = 104/4540 ms (T2W). For axial imaging, the acquisition settings were as follows: FOV = 160 × 160 mm, slice thickness = 4 mm, TE/TR = 100/4500 ms.

Diffusion tensor imaging

DTI protocol included DTI sequences in the axial plane with and without rFOV. Subjects were scanned in a supine position using a Sense XL Torso coil. The cFOV DTI and rFOV were performed using a special sensitivity array encoding technique, factor: 2; spectral-spatial radio frequency pulse and water excitation method; a diffusion-weighted spin echo single-shot echoplanar imaging with a free-breathing scanning technique; 11 different diffusion gradients; and a b value of 800 s mm⁻². For rFOV, Fov optimized and constrained undistorted single-shot, 2D spatially selective echoplanar RF excitation pulse was used. The 52 slices for cFOV and 16 slices for rFOV with contiguous 3 mm thickness were acquired covering from L5 to S1 nerve roots.

For cFOV, TR was 6000 ms, TE 74.5 ms, 4 excitations, FOV 320 × 256 mm, the matrix 96 × 192 and voxel size, 3.33 × 1.33 × 3 mm. Total acquisition time was 4 min 54 s.

For rFOV, TR was 6000 ms, TE 55.6 ms, 6 excitations, FOV 100 × 60 mm, the matrix 68 × 34 and voxel size, 1.47 × 1.76 × 3 mm. Total acquisition time was 7 min 18 s.

Image analysis

TrackVis (Department of Radiology, Massachusetts General Hospital, Boston, MA, USA) and Functool software (GE Healthcare UK Ltd, Little Chalfont, England) was used in DTI image analyses. rFOV with local excitation was compared with DTI with conventional cFOV.

Tractography was determined after selecting the left L5 nerve intracanal, foramina and extraforamina as three regions of interest (ROIs).

FA map and ADC map, and tractography quality was scored on a scale from 1 to 5 (1, No root; 2, poor; 3, satisfactory; 4, good; 5, excellent).

Intraindividual reliability was determined by the first author (HK) measuring FA and ADC values 1 week apart on two occasions in three ROI, the intracanal, foramina and extraforamina

Figure 1. SNR values were measured using $b=0$ images. ROIs were placed in the right psoas muscle (a), spinal canal (b) and left psoas muscle (c) in the rFOV images at the L4-5 level. ROIs were placed on the right psoas muscle (d), spinal canal (e) and left psoas muscle (f) in the cFOV images at the L4-5 level. T_2 weighted cube images which is isotropic volume imaging at same L4/5 level (g).

of the left L5 nerves. Interindividual reliability between 2 spine surgeons (HK and KA) who were well-experienced in DTI was measured using the same method.

ROIs were placed on the spinal canal, the left and right iliopsoas muscles at the L4-5 level on the $b=0$ images and SNR values were measured (Figure 1). The SNR was calculated using a single ROI¹⁸⁻²¹ as follows: $SNR = SI$ (signal intensity)/SD (standard deviation).

Statistical analyses

A Student's t -test was used to compare the image qualities with conventional methods. Intraindividual and interindividual reliabilities were tested using Spearman's correlation coefficient. Statistical analyses were performed using JMP Pro 12.0.1 (SAS Institute Inc., Cary, NC), and $p < 0.05$ was considered statistically significant. Results are presented as means $\pm$ SD.

RESULTS

In all cases, tractography with rFOV provided clearer images of the L5 and S1 nerve than cFOV. Image qualities with tractography (Figure 2) were rFOV: 4.80 ± 0.02 , and conventional method: 2.00 ± 0.03 ($p < 0.05$), while FA map (Figure 3a,b) showed rFOV: 4.50 ± 0.04 and conventional method: 1.40 ± 0.03 ($p < 0.05$) and ADC map (Figure 3c,d) showed rFOV: 4.80 ± 0.03 and conventional method: 1.60 ± 0.02 ($p < 0.05$), revealing significantly higher quality with rFOV over cFOV.

FA values and ADC values of L5 nerves in healthy volunteers were shown in Table 1.

FA values (intracanal, foramina, extraforamina) with rFOV were 0.301, 0.333 and 0.363, and FA values with cFOV were 0.401,

0.442 and 0.472, increasing as sites became more distal. ADC values (intracanal, foramina, extraforamina) with rFOV were $1.311 \text{ mm}^2 \text{ s}^{-1}$, $1.212 \text{ mm}^2 \text{ s}^{-1}$ and $1.114 \text{ mm}^2 \text{ s}^{-1}$ and ADC values with cFOV were $1.975 \text{ mm}^2 \text{ s}^{-1}$, $1.520 \text{ mm}^2 \text{ s}^{-1}$ and $1.295 \text{ mm}^2 \text{ s}^{-1}$ with values decreasing as sites grew distal. FA values and ADC values (intracanal, foramina, extraforamina) with rFOV were significantly higher compared with cFOV ($p < 0.05$).

With cFOV, the fibre counts were too low to allow imaging of the nerve root. Intraindividual reliability (rFOV vs conventional method) showed the following FA values ($r = 0.983$ vs 0.980 ; $p = 0.302$) and ADC values (0.960 vs 0.885 ; $p < 0.05$). Although FA values failed to reach statistical significance, the ADC values were significantly different. Interindividual reliability (rFOV vs conventional method) FA values ($r = 0.948$ vs 0.891 ; $p < 0.05$) and ADC values (0.974 vs 0.797 ; $p < 0.05$) revealed that compared with the conventional method, rFOV was more reliable.

In the spinal canal, SNR values were 4.866 ± 3.703 for rFOV and 1.840 ± 0.777 for cFOV, showing a significantly high SNR with rFOV compared with cFOV.

In the left iliopsoas muscle, SNR values were 4.203 ± 1.800 for rFOV and 4.584 ± 1.537 for cFOV. In the right iliopsoas muscle, SNR values were 4.429 ± 1.843 for rFOV and 5.166 ± 0.913 for cFOV. No significant difference was found between SNR values of rFOV and cFOV in the iliopsoas muscles (Figure 4).

Tractography of a patient with L5 lumbar foraminal stenosis

A 54-year-old male began experiencing lumbar pain and left lower limb pain (and right hip pain) from 2 years earlier.

Figure 2. Tractography of the L5 and S1 nerves in a healthy volunteer. (a) rFOV and (b) cFOV. Expanded images of the left L5 nerve at the same magnification. (c) rFOV and (d) cFOV. Fiber counts are higher with rFOV (a, c) vs cFOV (b, d) allowing for clearer imaging of the lumbar nerve.

Intermittent claudication occurred after 15 min walking. There was no bladder or rectal disturbance. Although muscle weakness was not admitted, a mild sensory disturbance was observed in the dorsum of both feet. The Japanese Orthopedic Association score was 15 points (normal score, 29 points).

MRI revealed left lumbar foraminal stenosis (Figure 5), and left L5 nerve root block was performed to confirm reproducibility. Although nerve imaging was difficult using the conventional method, the rFOV method clearly revealed L5 nerve disruption on tractography in the foramina (Figure 6a,c). In addition, the

Figure 3. Axial FA map (a, b) and ADC map (c, d) at L4/5 level in a healthy volunteer (a, c) rFOV (b, d) cFOV FA map and ADC map quality is higher with rFOV allowing for clearer imaging of the nerve root (arrow head) and spinal canal (arrow).

Table 1. FA values and ADC values of L5 nerves in healthy volunteers

	Intracanal	Foramina	Extraforamina
FA value			
rFOV	0.301 ± 0.085	0.333 ± 0.042	0.363 ± 0.069
cFOV	0.401 ± 0.041	0.442 ± 0.045	0.472 ± 0.016
<i>p</i> -value	0.0026	0.00002	0.0001
ADC value			
rFOV	1.311 ± 0.093	1.212 ± 0.085	1.114 ± 0.055
cFOV	1.975 ± 0.348	1.520 ± 0.275	1.295 ± 0.181
<i>p</i> -value	0.00002	0.003	0.007

FA values (intraspinal zone, nerve root zone and extraforaminal zone) were 0.406, 0.321 and 0.294 on the affected side and 0.423, 0.444 and 0.405 on the unaffected side.

TrackVis allowed expression of consecutive changes in FA values in colours (Figure 6e,f), ranging from no injury (FA normal: white) to injured (FA decreased: orange) allowing visualization of the degree of nerve injury (Figure 6g). rFOV image (e) allowed higher tract fiber counts and clearer image of L5 lumbar nerve compared with cFOV image (f) using TrackVis.

Compared with the healthy side, the affected side could be visualized with a decrease in FA values (orange) related to the compressed area (Figure 6e).

DISCUSSION

Although there are few reports on DTI in lumbar nerve roots,^{22–25} the number of lumbar nerve DTI studies has sharply increased in recent years.^{26,27} Balbi et al²² used Fiber Viewer to consecutively

Figure 5. T_2 weighted MR images of the patient with left L5 lumbar foraminal stenosis. (a) Central sagittal image and (b) parasagittal image. The white arrow indicates left L5 foraminal stenosis.

measure parameters along the fibre bundle and found that FA values showed sudden drops at the compressed site while ADC values increased. Takagi et al¹⁰ demonstrated that the FA values of the peripheral nerves were more strongly correlated with the axonal degeneration and regeneration in rat and mouse sciatic nerves. Generally, increased ADC may be owing to inflammation or oedema, whereas decreased FA may reflect damaged tissue microstructure, demyelination, axonal loss or increase in isotropic water volume.¹⁰

In this study, in intact nerves, FA values (intracanal, foramina, extraforamina) with rFOV were 0.301, 0.333 and 0.363, and FA values with cFOV were 0.401, 0.442 and 0.472. Our FA values are comparable with those obtained in the study of lumbar nerve roots by Balbi et al²² (0.218), van der Jagt et al²³ (0.31) and Budzik et al²⁴ (0.38).

Figure 4. SNR values from the cFOV (red bar) and rFOV (blue bar). In the spinal canal, SNR values were 4.866 ± 3.703 for rFOV and 1.840 ± 0.777 for cFOV, showing significantly higher SNR with a rFOV compared with cFOV. In the left iliopsoas muscle, SNR values were 4.203 ± 1.800 for rFOV and 4.584 ± 1.537 for cFOV. In the right iliopsoas muscle, SNR values were 4.429 ± 1.843 for rFOV and 5.166 ± 0.913 for cFOV. No significant difference was found between SNR values of rFOV and cFOV in the iliopsoas muscles. cFOV, conventional field of view; rFOV, reduced field of view; SNR, signal-to-noise ratio.

Figure 6. Tractography (a–d: using Functool software, e: using TrackVis) of the patient with left L5 lumbar foraminal stenosis. (a) rFOV image, (b) cFOV image, (c) expanded images of rFOV and (d) expanded images of cFOV. The rFOV images (a, c) clearly show signs of nerve pinching at the L5 foramen (white arrow). rFOV image (e) allowed higher tract fiber counts and clearer image of L5 lumbar nerve compared with cFOV image (f) using TrackVis. (g, e) No injury (FA value normal: white) to injury (FA value decreased: orange) and FA values are expressed in colours to show the compressed region in orange, indicating decreased FA (white arrowhead).

In patients with lumbar foraminal stenosis, a nerve root or spinal nerve is entrapped in a narrowed lumbar foramen as the result of a degenerative lumbar spinal disorder.²⁸

Macnab *et al*²⁹ appropriately named lumbar foraminal stenosis the “hidden zone,” as it is often overlooked. Even today, despite the progress in diagnostic imaging, we still struggle

with diagnoses that may result in postoperative failure of back surgery.³⁰

We have seen loss of the tract in lumbar foraminal stenosis in DTI, and FA values have been reported to drop. Moreover, changes in parameters (low FA, high ADC values) were observed in double-crush lesions. These parameters are dependent on the compressed areas which lead to nerve damage over a broad range from within the spinal column to the extraforaminal zone.²⁷

Miyagi et al³¹ assessed consecutive changes in FA and ADC values of normal lumbar nerve roots from the junction of the dura mater and demonstrated linear increases in FA values and linear decreases in ADC values. These are known to be affected by various factors such as the measurement method and partial volume effect.

In our study, we used TrackVis to express consecutive changes in FA values in colours allowing expression of the degree of nerve damage as “no damage” (FA normal value: white) to “damaged” (FA value decrease: orange). This method allows for direct visualization of consecutive changes in FA values and this method may break through measurement limits of ROI establishment such as partial volume effect.

However, since it is a high magnetic field, the magnetic susceptibility effect and increases in motion artefacts lead to signal irregularities and image distortion so that nerve fibre follow-up would be limited in areas with artefacts. In the future, further improvements in image resolution are essential for clinical applications.

rFOV DTI of the spinal cord enables the acquisition of high resolution images with which to evaluate specific spinal cord tracts and distinguish white matter from grey matter. Maki et al¹⁶ showed correlations between FA of specific white matter in the spinal cord tracts and severity of myelopathy in patients with cervical compression myelopathy using rFOV DTI.

Budzik et al¹⁷ reported that rFOV imaging of asymptomatic volunteers was essential to achieving DTI imaging and tractography of the lumbar nerve roots in 3 T, enabling a drastic reduction of the susceptibility and chemical shift artefacts that impeded accurate tractography on cFOV imaging.

We compared rFOV with conventional methods in lumbar nerves in healthy volunteers and patients with degenerative lumbar disorders. Compared with conventional methods, rFOV enabled clearer imaging of lumbar nerves on tractography and FA maps, and ADC maps. In addition, in lumbar nerve compression, rFOV allowed for clear imaging of the compressed area compared with conventional methods. Both intraindividual reliability and interindividual reliability of FA and ADC values were higher with the rFOV method. Significantly higher SNR was obtained with rFOV compared with cFOV in the spinal canal.

In the future, rFOV methods can be applied to various lumbar disc disorders such as vertebral foraminal stenosis allowing for visualization of nerve disorders, and improved quantification.

We acknowledge that our study has several limitations. The first is that a small number of subjects were investigated. Second, restriction of FOV limited the number of nerve roots that could be imaged compared with conventional methods. Finally, healthy volunteers were much younger than patients that may make bias and affect the results, but we did not compare DTI parameters between healthy volunteers and patients in this study. Further studies are needed to investigate whether our findings remain valid in a large population.

CONCLUSIONS

We attempted high quality imaging of lumbar nerves using rFOV using 3 T MRI in healthy volunteers and patients with degenerative lumbar disorders. Compared with traditional methods, rFOV allows for clear imaging of the lumbar nerve and enables accurate measurements of the FA and ADC values. Significantly higher SNR was obtained using rFOV compared with cFOV in the spinal canal. High resolution DTI with rFOV may be used to visualize nerve entrapments and allow for more accurate diagnosis of DTI parameter quantification with opportunities for clinical applications.

ACKNOWLEDGMENTS

This work was supported by the General Insurance Association of Japan grant.

REFERENCES

1. Basser PJ, Jones DK. Diffusion-tensor MRI: theory, experimental design and data analysis - a technical review. *NMR Biomed* 2002; 15(7-8): 456–67. doi: <https://doi.org/10.1002/nbm.783>
2. Beaulieu C, Allen PS. Determinants of anisotropic water diffusion in nerves. *Magn Reson Med* 1994; 31: 394–400. doi: <https://doi.org/10.1002/mrm.1910310408>
3. Beaulieu C, Does MD, Snyder RE, Allen PS. Changes in water diffusion due to Wallerian degeneration in peripheral nerve. *Magn Reson Med* 1996; 36: 627–31. doi: <https://doi.org/10.1002/mrm.1910360419>
4. Basser PJ, Pierpaoli C. Microstructural and physiological features of tissues elucidated by quantitative-diffusion-tensor MRI. *J Magn Reson B* 1996; 111: 209–19. doi: <https://doi.org/10.1006/jmrb.1996.0086>
5. Minematsu K, Li L, Fisher M, Sotak CH, Davis MA, Fiandaca MS. Diffusion-weighted magnetic resonance imaging: rapid and quantitative detection of focal brain ischemia. *Neurology* 1992; 42: 235–40. doi: <https://doi.org/10.1212/WNL.42.1.235>
6. Lin X, Tench CR, Morgan PS, Constantinescu CS. Use of combined conventional and quantitative MRI to quantify pathology related to cognitive impairment in multiple sclerosis. *J Neurol Neurosurg Psychiatry* 2008; 79: 437–41. doi: <https://doi.org/10.1136/jnnp.2006.112177>

7. Mamata H, Jolesz FA, Maier SE. Apparent diffusion coefficient and fractional anisotropy in spinal cord: age and cervical spondylosis-related changes. *J Magn Reson Imaging* 2005; **22**: 38–43. doi: <https://doi.org/10.1002/jmri.20357>
8. Khalil C, Hancart C, Le Thuc V, Chantelot C, Chechin D, Cotten A. Diffusion tensor imaging and tractography of the median nerve in carpal tunnel syndrome: preliminary results. *Eur Radiol* 2008; **18**: 2283–91. doi: <https://doi.org/10.1007/s00330-008-0971-4>
9. Lehmann HC, Zhang J, Mori S, Sheikh KA. Diffusion tensor imaging to assess axonal regeneration in peripheral nerves. *Exp Neurol* 2010; **223**: 238–44. doi: <https://doi.org/10.1016/j.expneurol.2009.10.012>
10. Takagi T, Nakamura M, Yamada M, Hikishima K, Momoshima S, Fujiyoshi K, et al. Visualization of peripheral nerve degeneration and regeneration: monitoring with diffusion tensor tractography. *Neuroimage* 2009; **44**: 884–92. doi: <https://doi.org/10.1016/j.neuroimage.2008.09.022>
11. Mac Donald CL, Dikranian K, Bayly P, Holtzman D, Brody D. Diffusion tensor imaging reliably detects experimental traumatic axonal injury and indicates approximate time of injury. *J Neurosci* 2007; **27**: 11869–76. doi: <https://doi.org/10.1523/JNEUROSCI.3647-07.2007>
12. Eguchi Y, Ohtori S, Orita S, Kamoda H, Arai G, Ishikawa T, et al. Quantitative evaluation and visualization of lumbar foraminal nerve root entrapment by using diffusion tensor imaging: preliminary results. *AJNR Am J Neuroradiol* 2011; **32**: 1824–9. doi: <https://doi.org/10.3174/ajnr.A2681>
13. Saritas EU, Cunningham CH, Lee JH, Han ET, Nishimura DG. DWI of the spinal cord with reduced FOV single-shot EPI. *Magn Reson Med* 2008; **60**: 468–73. doi: <https://doi.org/10.1002/mrm.21640>
14. Zaharchuk G, Saritas EU, Andre JB, Chin CT, Rosenberg J, Brosnan TJ, et al. Reduced field-of-view diffusion imaging of the human spinal cord: comparison with conventional single-shot echo-planar imaging. *AJNR Am J Neuroradiol* 2011; **32**: 813–20. doi: <https://doi.org/10.3174/ajnr.A2418>
15. Park EH, Lee YH, Jeong EK, Roh YH, Suh JS. Diffusion tensor imaging focusing on lower cervical spinal cord using 2D reduced FOV interleaved multislice single-shot diffusion-weighted echo-planar imaging: comparison with conventional single-shot diffusion-weighted echo-planar imaging. *Magn Reson Imaging* 2015; **33**: 401–6. doi: <https://doi.org/10.1016/j.mri.2015.01.007>
16. Maki S, Koda M, Ota M, Oikawa Y, Kamiya K, Inada T, et al. Reduced field-of-view diffusion tensor imaging of the spinal cord shows motor dysfunction of the lower extremities in patients with cervical compression myelopathy. *Spine* 2015; **1**. doi: <https://doi.org/10.1097/BRS.0000000000001123>
17. Budzik J-F, Vercllytte S, Lefebvre G, Monnet A, Forzy G, Cotten A. Assessment of reduced field of view in diffusion tensor imaging of the lumbar nerve roots at 3 T. *Eur Radiol* 2013; **23**: 1361–6. doi: <https://doi.org/10.1007/s00330-012-2710-0>
18. Froeling M, Nederveen AJ, Nicolay K, Strijkers GJ. DTI of human skeletal muscle: the effects of diffusion encoding parameters, signal-to-noise ratio and T2 on tensor indices and fiber tracts. *NMR Biomed* 2013; **26**: 1339–52. doi: <https://doi.org/10.1002/nbm.2959>
19. Lagan M, Rovaris M, Ceccarelli A, Venturelli C, Marini S, Baselli G. DTI parameter optimisation for acquisition at 1.5T: SNR analysis and clinical application. *Comput Intell Neurosci* 2010; **254032**.
20. Landman BA, Farrell JA, Jones CK, Smith SA, Prince JL, Mori S. Effects of diffusion weighting schemes on the reproducibility of DTI-derived fractional anisotropy, mean diffusivity, and principal eigenvector measurements at 1.5T. *Neuroimage* 2007; **36**: 1123–38. doi: <https://doi.org/10.1016/j.neuroimage.2007.02.056>
21. Kaufman L, Kramer DM, Crooks LE, Ortendahl DA. Measuring signal-to-noise ratios in MR imaging. *Radiology* 1989; **173**: 265–7. doi: <https://doi.org/10.1148/radiology.173.1.2781018>
22. Balbi V, Budzik JF, Duhamel A, Bera-Louville A, Le Thuc V, Cotten A. Tractography of lumbar nerve roots: initial results. *Eur Radiol* 2011; **21**: 1153–9. doi: <https://doi.org/10.1007/s00330-010-2049-3>
23. van der Jagt PK, Dik P, Froeling M, Kwee TC, Nievelstein RA, ten Haken B, et al. Architectural configuration and microstructural properties of the sacral plexus: a diffusion tensor MRI and fiber tractography study. *Neuroimage* 2012; **62**: 1792–9. doi: <https://doi.org/10.1016/j.neuroimage.2012.06.001>
24. Budzik JF, Vercllytte S, Lefebvre G, Monnet A, Forzy G, Cotten A. Assessment of reduced field of view in diffusion tensor imaging of the lumbar nerve roots at 3 T. *Eur Radiol* 2013; **23**: 1361–6. doi: <https://doi.org/10.1007/s00330-012-2710-0>
25. Dallaudière B, Lincot J, Hess A, Balbi V, Cornelis F, Larbi A, et al. Clinical relevance of diffusion tensor imaging parameters in lumbar disco-radicular conflict. *Diagn Interv Imaging* 2014; **95**: 63: 63: 688. doi: <https://doi.org/10.1016/j.diii.2013.08.019>
26. Eguchi Y, Kanamoto H, Oikawa Y, Suzuki M, Yamanaka H, Tamai H, et al. Recent advances in magnetic resonance neuroimaging of lumbar nerve to clinical applications: a review of clinical studies utilizing diffusion tensor imaging and diffusion-weighted magnetic resonance neurography. *Spine Surg Related Res* 2017; **1**: 61–71. doi: <https://doi.org/10.22603/ssrr.1.2016-0015>
27. Kanamoto H, Eguchi Y, Suzuki M, Oikawa Y, Yamanaka H, Tamai H, et al. The diagnosis of double-crush lesion in the L5 lumbar nerve using diffusion tensor imaging. *Spine J* 2016; **16**: 315–21. doi: <https://doi.org/10.1016/j.spinee.2015.11.003>
28. Jenis LG, An HS. Spine update. Lumbar foraminal stenosis. *Spine* 2000; **25**: 389–94.
29. Macnab I. Negative disc exploration. An analysis of the causes of nerve-root involvement in sixty-eight patients. *J Bone Joint Surg Am* 1971; **53**: 891–903.
30. Burton R, Kirkaldy-Willis W, Yong-Hing K, Heithoff KB. Causes of failure of surgery on the lumbar spine. *Clin Orthop* 1981; **157**: 191–7.
31. Miyagi R, Sakai T, Yamabe E, Yoshioka H. Consecutive assessment of FA and ADC values of normal lumbar nerve roots from the junction of the dura mater. *BMC Musculoskelet Disord* 2015; **16**: 156. doi: <https://doi.org/10.1186/s12891-015-0576-4>