Radicul compression syndromes play a central role in the pathophysiology of spinal diseases. Symptoms of pain syndromes are often atypical and the assignment to dermatomes may be difficult or deficient. Despite the substantial progress in medical imaging, discrepancies between symptoms and imaging findings may be significant. Patients with large space-occupying lesions frequently have minor symptoms, whereas others show major symptoms without morphological findings on imaging; this was confirmed by results from a study using an animal model. Improvements in sectional imaging techniques have to produce a reduction of the discrepancies between symptoms and morphological imaging findings.

Lumbar myelography was accepted as the gold standard of detecting radicular compression syndromes for a long time. However, the diagnostic performance of this invasive method is limited, and undesirable side effects are not uncommon, such as an allergic reaction to the contrast agent or infections. The invention of CT allowed for combining conventional myelography with a digital sectional imaging technique (postmyelographic CT). Comparative studies by Raininko and Kampmann demonstrated the advantages of this technique.

Magnetic resonance imaging, a method with excellent soft-tissue contrast, was initially used for diagnosis of intraspinal masses, especially for neuronal compression...
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Magnetic Resonance Myelography

Magnetic resonance imaging examinations were performed within 2 days after myelography on a 1.5-T whole-body MRI machine (Sonata; Siemens) equipped with a 6-channel spine array coil, with the patient supine. For MR myelography we used a dedicated MR sequence, a 3D heavily T2-weighted half-Fourier acquisition single-shot turbo spin-echo (HASTE) sequence with the following parameters: TR 10,000 msec, TE 165 msec, slice thickness 0.5 mm, flip angle 180°, voxel size 0.5 × 0.5 × 0.5 mm³, matrix size 256 × 256, and FOV 120 × 120 mm². Orientation of the volume of interest, as well as phase encoding direction, was coronal. The acquisition time of this dedicated MR myelography sequence was 10 minutes. The sequence scheme included frequency-selective fat suppression and coronal saturation pulses to suppress motion artifacts due to breathing. Additionally, “partial Fourier” was used (that is, 4/8 of the k-space was sampled) to suppress anatomical structures in the vicinity of the CSF and the dural sac. In so doing, the central structures remained unaltered and fully visible, whereas the contrast resolution decreased with increasing distance to the central structures. However, the advantage of an enhanced CSF signal comes with the drawback of loss of anatomical information in the HASTE data. A sagittal T2-weighted turbo spin echo sequence was used as an anatomical-basis data set, an MR data set with anatomical information that was used as the basis data set for image fusion of the MR myelography. The parameters of the sequence were TR 4000 msec, TE 120 msec, slice thickness 2 mm, FOV 250 × 250 mm², matrix size 256 × 256, and acquisition time 2.5 minutes.

Image Data Postprocessing and Evaluation

Coronal sections were calculated from the postmyelographic CT data using multiplanar reconstruction. For each lumbar vertebra the midline of the intervertebral disc was defined as a sectional plane on these images. From this axial section plane along the midline of the intervertebral disc, 4 sectional planes above and 4 sectional planes below were defined in parallel to the central plane, with a section thickness of 2 mm each. Multiplanar reconstruction resulted in 9 axial slices around the intervertebral disc.

To determine exact anatomical information within the MR myelography data, the 3D HASTE data sets were fused to the corresponding sagittal T2-weighted turbo spin echo data set. This procedure was performed on a commercially available workstation (Leonardo; Siemens) using the “3D fusion” tool. Section planes along the midline of the intervertebral disc, in the same orientation as described for the postmyelographic CT and multiplanar reconstruction, were used for reformatting to obtain 9 axial slices around the intervertebral disc. The slice thickness of these axial MR myelography images was also 2 mm.

The dural area was manually defined on the 9 axial images of both the postmyelographic CT and MR myelography data in an interdisciplinary manner, using an experienced neuroradiologist, an experienced neurosurgeon, and an experienced medical physicist in consensus. The values of the dural area for the central axial image plane were used for comparisons of dural cross-sectional areas

Methods

Study Population

Fifty patients with suspected lumbar spinal stenosis and referred for lumbar myelography and postmyelographic CT were also evaluated with our improved MR myelography protocol. There were 15 women and 35 men, ranging in age from 36 to 82 years old (mean ± SD = 61.4 ± 12.0 years). All patients suffered from lower back pain and had neurological symptoms (radicular deficits and/or neurogenic claudication [claudicatio spinalis]). The procedures were explained to the patients and written informed consent was obtained from all patients before the procedures as required by the local institutional review board.

Myelography and Postmyelographic CT

Conventional myelography was performed while patients were prone. The nonionic contrast agent (10 ml Isovist 300 and 5 ml Isovist 240; Schering AG) was applied intrathecally at the levels where the stenoses were assumed. To achieve optimal distribution of the contrast agent in patients with an incomplete allocation of the agent within the range of the stenosis, an abdominal press, the flexion (bent forward) sitting position, and waiting periods of up to 1 hour were applied. To display the lumbar region, 3 standard projections were obtained with anteroposterior, lateral, and left anterior oblique or right anterior oblique orientation. In patients with suspicion of spinal stenosis and an incomplete or complete contrast block on conventional myelography, a postmyelographic CT examination was additionally performed within the following 2 hours using a multislice spiral CT scan (Volume Zoom; Siemens). Contiguous with the stenotic level of the myelography in the postmyelographic CT examination, the subsequent upper and lower levels were examined. The examination was performed while the patient was prone, with breath-holding.
between postmyelographic CT and MR myelography. The area values of all 9 image planes were used for calculation of the dural sac volume. Figure 1 shows the postprocessing steps of both the postmyelographic CT (Fig. 1 upper) and MR myelography (Fig. 1 lower) data for a normal lumbar level: multiplanar reconstruction of the 9 axial slices (Fig. 1 left column), and segmentation of the dural areas (Fig. 1 right column).

**Statistical Methods**

Data were analyzed using SPSS statistical software (version 14.0; SPSS Inc.). To compare differences in dural area and volume between postmyelographic CT and MR myelography, we used a 2-sided paired Student t-test for all levels combined, and a Wilcoxon signed-rank test for individual lumbar levels. Comparisons of dural area and volume in normal levels and in levels with stenosis were performed using a 2-sided Mann-Whitney U-test. The 99% CI was calculated for levels with no pathological changes and stenotic levels in patients with claudication distances less than 100 meters. Pearson correlation coefficients were calculated for measuring relationships between dural area and volume assessed with postmyelographic CT and MR myelography. Correlation coefficients were interpreted under consideration of the specifications given by Zou et al.\(^{27}\) For all tests, the level of significance was set at \( p < 0.05 \).

**Results**

A total of 180 lumbar levels (L1–2 to L5–S1) were evaluated in the 50 patients (mean 3.6 levels per patient, range 2–5 levels) who were suspected to suffer from a stenosis of the lumbar spinal canal. No pathological changes were found on 88 levels in 41 patients. Eleven normal areas were found at L1–2, 19 at L2–3 and L3–4, 15 at L4–5, and 24 at L5–S1. Spinal canal stenoses were detected on 92 levels in 41 patients (31 patients with a claudication distance < 100 meters). Nine patients showed no lumbar spinal canal stenoses. No stenoses were detected at L1–2. Twelve areas with stenoses were found at L2–3, 25 at L3–4, 34 at L4–5, and 21 at L5–S1. Figure 2 shows the postprocessing results of both the postmyelographic CT (Fig. 2 upper) and MR myelography (Fig. 2 lower) data for a patient with stenosis at L3–4.

**Comparison and Correlation of Dural Areas**

The mean value of the 88 normal dural areas on postmyelographic CT was 169.8 ± 47.6 mm\(^2\), and on MR myelography was 170.8 ± 46.8 mm\(^2\). These mean values were not significantly different according to a 2-sided paired Student t-test. Analyzed according to lumbar level, we found no significant differences in normal dural areas between postmyelographic CT and MR myelography for all levels (L1–2 to L5–S1). The areas on MR myelography were slightly larger, ranging between 0.0 (0%, at L1–2) and 1.9 mm\(^2\) (1.2%, at L4–5) larger (Fig. 3 upper).

The mean dural area of the 92 levels with stenosis on postmyelographic CT was 83.2 ± 34.0 mm\(^2\) and on MR myelography was 94.0 ± 33.1 mm\(^2\). These mean values were significantly different (\( p = 0.001 \)). Analyzed accord-
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The mean dural volume of the 92 levels with stenosis on postmyelographic CT was $1794.1 \pm 600.5 \text{ mm}^3$, and on MR myelography was $1968.0 \pm 552.4 \text{ mm}^3$. These mean values were also significantly different ($p = 0.001$). Analyzed according to lumbar level, we found significant differences between postmyelographic CT and MR myelography for all levels (Fig. 4 lower): L2–3 (difference of $115.7 \text{ mm}^3$, 5.8%; $p = 0.041$), L3–4 (difference of $172.6 \text{ mm}^3$, 8.9%; $p = 0.03$), L4–5 (difference of $189.9 \text{ mm}^3$, 9.3%; $p = 0.001$), and L5–S1 (difference of $183.1 \text{ mm}^3$, 9.9%; $p = 0.021$).

As with normal areas, Pearson correlation revealed a strong correlation between normal dural volumes on postmyelographic CT and MR myelography for the entirety of levels as well as for all individual levels. For levels with stenosis we found a moderate correlation for the entirety of levels and for all individual levels (Table 1).

Comparison of Normal Levels and Levels With Stenosis

As expected, both dural areas and volumes for postmyelographic CT and MR myelography were significantly different ($p < 0.001$ each) between normal levels and levels with stenosis using a Mann-Whitney U-test. The 99% CIs for dural areas and volumes of normal and stenotic levels (in patients with claudication distances < 100 meters) are shown in Table 2.

Discussion

Several studies in the literature have compared conventional myelography, postmyelographic CT, and MR myelography. Kuroki et al. investigated 40 patients with symptoms of lumbar nerve root compression using conventional and MR myelography. They found that both depiction of intradural structures and image quality were comparable. Studies by Eberhardt et al. even demonstrated advantages of MR myelography compared with conventional myelography in combination with postmyelographic CT, particularly in the detection of extreme lumbar spinal canal stenoses. In a cohort of 275 patients, Ferrer et al. found that MR myelography improved diagnostic accuracy in 16.7% of cases. Studies from Bartlett et al., Birchall et al., Melhem, and Wang et al. supported these findings. Selection of the appropriate MR sequence technique is essential. Gradient echo sequences were primarily used for heavily T2-weighted MR sequences thus far. However, these sequences are prone to susceptibility artifacts, especially in structures with varying proton density. This drawback can be reduced by using spin echo sequences, which additionally have the advantage of a higher signal-to-noise ratio.

In this study, we went one step further and used an improved 3D turbo spin echo sequence (3D HASTE) in combination with “partial Fourier” (collecting only the

![Fig. 3. Comparison between postmyelographic CT and MR myelography of the dural sac cross-sectional area for normal lumbar levels (upper) and lumbar levels with stenosis (lower). Asterisk = significant differences ($p < 0.05$) between mean values.](image-url)
central parts of the k-space), and frequency selective fat suppression, to improve background contrast and avoid signal overlapping from adjacent structures, respectively. Additionally, this strategy is associated with a reduction of breathing artifacts. We found no significant differences in normal lumbar levels and strong correlations for both dural areas and volumes between postmyelographic CT and MR myelography. The lower lumbar levels (L4–5 and L5–S1) showed significantly larger areas on MR myelography when compared with postmyelographic CT, but not for the upper levels (L2–3 and L3–4). Dural volume revealed significantly larger values for MR myelography at all 4 lumbar levels with stenoses in our cohort (L2–3 to L5–S1). Both dural area and volume of levels with stenoses showed no to minor correlation between postmyelographic CT and MR myelography. Furthermore, the upper limits of the 99% CIs for dural areas and volumes for stenotic levels in patients with claudication distance of less than 100 meters (Table 2) can be interpreted as limit values and an indication for surgical treatment.

Our values for the cross-sectional areas of the dural sac of normal lumbar levels are in agreement with previously published findings, although their values are tendentially lower. The authors investigated the effect of body position and axial load on dural sac cross-sectional area using conventional MRI, with the result that horizontal MRI with the patient supine and the legs straightened was comparable to vertical MRI, whether axial compression was added or not. This finding stands in marked contrast to the findings of Kanno et al. These discrepancies might be explained by the differences in the conventional MR protocols (TR, TE, slice thickness, and others) used in the studies, and that only dural areas but not dural volumes were evaluated. Although it is more laborious, the determination of dural volumes has the advantage of allowing for compensation of even minor differences and inaccuracies in slice positioning and orientation. The usefulness and advantages of dedicated MR myelography sequences have been demonstrated previously. Dorenbeck et al. compared a T2*-weighted, 2D, spoiled gradient echo multiecho sequence with magnetization transfer saturation pulse, with lumbar myelography and postmyelographic CT. They found that this gradient echo sequence was as accurate as postmyelographic CT in evaluating osteophytes and narrowing of the neural foramina. Eberhardt et al. compared conventional myelography and postmyelographic CT with MR myelography using a fat-suppressed 3D fast imaging with steady precession sequence for diagnosis of the lumbar root compression syndrome. They found that compared with the conventional method, MR myelography showed comparable sensitivity in the visualization of the spinal nerve roots in the lumbar spine, and MR myelography had significant advantages, especially in

### TABLE 1: Correlation of dural areas and volumes from postmyelographic CT and MR myelography

<table>
<thead>
<tr>
<th>Lumbar Level</th>
<th>All</th>
<th>L1–2</th>
<th>L2–3</th>
<th>L3–4</th>
<th>L4–5</th>
<th>L5–S1</th>
</tr>
</thead>
<tbody>
<tr>
<td>normal areas</td>
<td>0.975‡</td>
<td>0.992‡</td>
<td>0.942‡</td>
<td>0.984‡</td>
<td>0.987‡</td>
<td>0.980‡</td>
</tr>
<tr>
<td>areas w/ stenosis</td>
<td>0.582‡</td>
<td>NA</td>
<td>0.333</td>
<td>0.772‡</td>
<td>0.562‡</td>
<td>0.594‡</td>
</tr>
<tr>
<td>normal volumes</td>
<td>0.966‡</td>
<td>0.968‡</td>
<td>0.991‡</td>
<td>0.985‡</td>
<td>0.992‡</td>
<td>0.957‡</td>
</tr>
<tr>
<td>volumes w/ stenosis</td>
<td>0.733‡</td>
<td>NA</td>
<td>0.676‡</td>
<td>0.654‡</td>
<td>0.819‡</td>
<td>0.796‡</td>
</tr>
</tbody>
</table>

* All values are correlation coefficients. NA = not applicable.
† Significant correlation at p < 0.05.
‡ Significant correlation at p < 0.001.

![Fig. 4](image-url)
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**TABLE 2: Confidence intervals (99%) for dural areas and volumes from postmyelographic CT and MR myelography**

<table>
<thead>
<tr>
<th>Area/Volume All</th>
<th>L1–2</th>
<th>L2–3</th>
<th>L3–4</th>
<th>L4–5</th>
<th>L5–S1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MR myelography areas (mm²)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>stenotic*</td>
<td>81–100</td>
<td>NA</td>
<td>62–123</td>
<td>73–106</td>
<td>76–103</td>
</tr>
<tr>
<td><strong>postmyelographic CT areas (mm²)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>stenotic*</td>
<td>67–87</td>
<td>NA</td>
<td>55–107</td>
<td>64–102</td>
<td>57–88</td>
</tr>
<tr>
<td><strong>MR myelography volumes (mm³)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>postmyelographic CT volumes (mm³)</strong></td>
<td></td>
<td></td>
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</tbody>
</table>

* Calculated for the 31 patients with claudication distances < 100 meters.

cases of extreme spinal canal stenosis. The differences in dural areas and volumes in this study might be explained by the fact that in a case of a severely compressed thecal sac, the viscosity of the intrathecally applied contrast agent is too high in the framework of myelography and that the gravitationally dependent component is too low to achieve sufficient fluid contrast.

**Conclusions**

An optimized MR myelography approach—a dedicated 3D MR myelography sequence in combination with image fusion—is required to achieve more a reliable diagnosis of lumbar spine stenoses compared with postmyelographic CT, especially in cases of severe compression. This approach may be helpful in preventing overestimation of lumbar spine stenoses. Upper limits of 99% CIs for stenotic levels can be interpreted as an indication for surgical treatment. Further studies that include postoperative outcomes are required, however.

**Disclosure**

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Eberhardt, Stadlbauer. Acquisition of data: Eberhardt, Ganslandt. Analysis and interpretation of data: all authors. Drafting the article: all authors. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Stadlbauer. Statistical analysis: Stadlbauer. Administrative/technical/material support: Eberhardt. Study supervision: Eberhardt.

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