Magnetic resonance imaging is established as the technique of choice for assessment of degenerative disorders of the lumbar spine. However, it is routinely performed with the patient supine and the hips and knees flexed. The absence of axial loading and lumbar extension results in a maximization of spinal canal dimensions, which may in some cases, result in failure to demonstrate nerve root compression. Attempts have been made to image the lumbar spine in a more physiological state, either by imaging with flexion–extension, in the erect position or by using axial loading. This article reviews the literature relating to the above techniques.

INTRODUCTION

Magnetic resonance imaging (MRI) is established as the technique of choice for assessment of degenerative disorders of the lumbar spine [1] and its role in the diagnosis of lumbar spinal stenosis has recently been reviewed [2–4]. However, it is routinely performed with the patient supine and the hips and knees flexed, resulting in relative lumbar flexion. With this technique, the absence of axial loading and lumbar extension results in a maximization of spinal canal dimensions, which may result in failure to demonstrate nerve root compression. The positional nature of lumbar spinal stenosis has been clearly demonstrated with functional CT myelography [5]. Attempts have been made to assess the lumbar spine in a more “physiological” state, either by imaging with flexion/extension [6,7], in the erect seated position [8–12], or using axial loading [13–19]. This article reviews the literature relating to the above techniques, with emphasis on axial loaded imaging using an MRI compatible compression device (Dynawell, Dynamed AB, Stockholm, Sweden) in a low field open scanner.

CADAVER STUDIES

The effect of applied stresses and positional changes related to the lumbar spine has been extensively reported in cadaver studies. Changes in central canal, lateral recess and inter-vertebral foraminal dimensions in different states of loading and position have been reported [20–23]. Nowicki et al. [20] assessed the effect of pure axial loading on the lumbar spine and found that compression resulted in reduction of central canal, lateral recess and foraminal dimensions, but did not increase the degree of nerve root displacement or compression. Inufusa et al. [21] assessed changes in central canal and foraminal dimensions between flexed, neutral and extended positions with the addition of axial compression. In the extended position, significant reduction of central canal area, mid-sagittal diameter and sub-articular diameter was seen, whereas the opposite was identified in the flexed position. Extension decreased all foraminal dimensions, whereas flexion increased all foraminal dimensions. Foraminal cross-sectional area was decreased in extension by an average of 15%, and increased in flexion by an average of 12% compared with the neutral position. Extension also results in an increase in the incidence of nerve root contact or compression by bulging intervertebral disc or ligamentum flavum. The incidence of root compression also increases with increasing disc degeneration [22]. Fujiwara et al. [23] further assessed the effects of lateral bending and axial rotation on foraminal dimensions and root compression.
and also the effects of extension and flexion on morphology of the disc and ligamentum flavum. The flexed position is associated with greatest foraminal cross-sectional area, as previously reported, and with the least bulging of the disc and thickness of the ligamentum flavum. The opposite is seen in the extended position. Axial rotation reduces foraminal width and area on the side of rotation, while increasing foraminal height and area on the opposite side. Similarly, lateral bending reduces foraminal dimensions and area on the side of bending, while increasing the same parameters on the opposite side.

**EFFECT OF LOADING ON THE NORMAL/ASYMPTOMATIC LUMBAR SPINE**

**Intervertebral Disc**

Beattie et al. [6] investigated changes in the position of the nucleus pulposus between flexion and extension in 20 asymptomatic volunteers using sagittal T2-weighted MR images. In the extended position, the distance from the posterior margin of the nucleus of normal discs from a line drawn between the posterior margins of the adjacent vertebral bodies increased compared with the flexed position. No change

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**Fig. 1** – Dynawell compression device, comprising a vest, which is connected to a foot-plate (large arrow) by two harnesses (small arrow). Compression is applied by loading the patient to 25% of body weight on each of the two dials on the foot-plate and maintained for 5 min before re-imaging.

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**Fig. 2** – Change in lumbar lordosis. (a) Sagittal T2-weighted fast spin-echo sequence without axial loading. The lordosis between L1 and S1 is measured at 59.1°. (b) Sagittal T2-weighted fast spin-echo sequence with axial loading. The lordosis between L1 and S1 is measured at 72.6°.
Fig. 3 – Changes in segmental lordosis at L3/4 and L5/S1. (a) Sagittal T2-weighted fast spin-echo sequence without axial loading. The lordosis measured at L3/4 is 6.2° and at L5/S1 is 34.0°. (b) Sagittal T2-weighted fast spin-echo sequence with axial loading. The lordosis measured at L3/4 is now 13.2° and at L5/S1 is 31.0°.

Fig. 4 – Change in lumbar spine vertical height. (a) Sagittal T2-weighted fast spin-echo sequence without axial loading. The height between L1 and S1 is measured at 201 mm. (b) Sagittal T2-weighted fast spin-echo sequence with axial loading. The height between L1 and S1 is measured at 196 mm.
was seen in the distance of the anterior disc margin from the front of the vertebral bodies. These findings suggest that the anteroposterior dimensions of the nucleus decrease with increase in lumbar lordosis. Such changes were not identified in degenerate discs.

Chung et al. [7] found no significant change in the shape or dimensions of the L3/4 and L4/5 discs when comparing flexion, extension and rotation with the patient supine. However, comparison between flexion and extension MRI in the erect position has demonstrated changes in disc morphology, with 27% of discs overall showing an increase in posterior annular bulging in the erect extended position. This percentage increased to 40% for degenerate discs [8].

Disc heights are affected by axial compression. The standardized technique for axially loaded MRI is to image the spine as for conventional MRI, with the patient supine and hips and knees flexed. This is followed by repeat imaging with the hips and knees extended, a small roll under the lumbar spine to produce slight lordosis and then compression to 50% of the patients body weight for 5 min using the Dynawell Compression device (Fig. 1) [16,17]. Using this technique, Kimura et al. [15] assessed changes in lumbar disc height during compression in eight asymptomatic young adults, finding a significant reduction of disc height only at the L4/5 level.

**Spinal Alignment**

Axial compression results in complex changes in spinal alignment, which can vary between motion segments. Kimura et al. [15] measured changes in intervertebral angles between the non-loaded position and during axial loading. Overall, there was a mild increase in lumbar lordosis between L1 and S1 (Fig. 2), which was consistent with changes that can be seen between supine and erect lumbar spine radiography. However, at individual disc levels, a significant increase in lordosis was seen only at L3/4, whereas axial loading actually resulted in a significant reduction in lordosis at L5/S1 (Fig. 3) and no change in angle at L4/5.

Morphological changes of lumbar spine sagittal alignment following axial compression were also investigated by Wisleder et al. [18]. These authors assessed changes in lumbar rotation, bending, compression and disc translation. In all cases, the lumbar spine underwent a reduction in height (Fig. 4), which averaged approximately 4 mm. This was mainly due to bending of the spine (increased lordosis). The L2–L4 levels underwent extension, whereas L5 became more flexed. The L2/3 to L4/5 discs translated forward, whereas the lumbosacral disc moved backwards. Posterior rotation of the sacrum was also seen (Fig. 5).

**Central Canal and Intervertebral Foraminae**

Several studies have investigated positional changes in central canal dimensions. Chung et al. [7] identified reduction of spinal canal sagittal dimensions and dural sac cross-sectional area (DCSA) in healthy subjects imaged in the supine position.
with extension and rotation. These positions also produced increased thickness of the ligamentum flavum. Reduction in central canal dimensions is also identified following imaging in the erect extended position, especially at degenerate disc levels [8]. Similar findings were recorded by Schmid et al. [10] who noted mean DCSA of 268 mm$^2$ in the upright flexed position, which reduced to 224 mm$^2$ in the upright extended position.

Axial loading with extension in the supine position also produces reductions in DCSA, which are most commonly seen at L4/5 and increase in frequency with increasing age (Fig. 6) [16].

As with central canal dimensions, foraminal dimensions are also reduced in the supine extension and the erect extended positions as compared with the flexed position [7,10]. The effect of axial loading on foraminal dimensions has not been studied in vivo.

Fig. 6 – Reduction of DCSA at normal L4/5 disc level. (a) Axial T1-weighted spin-echo sequence without axial loading. The DCSA is measured at 313 mm$^2$. (b) Axial T1-weighted spin-echo sequence with axial loading. The DCSA is measured at 241 mm$^2$.

Fig. 7 – Accentuation of disc herniation. Broad-based L5/S1 central and right paracentral disc prolapse with compression of the right S1 nerve root. (a) Axial T1-weighted spin-echo sequence without axial loading. The anteroposterior dimension of the disc prolapse is measured at 9.22 mm. Measurement is made from a line joining the base of the pedicles to the posterior margin of the disc prolapse. (b) Axial T1-weighted spin-echo sequence with axial loading. The anteroposterior dimension of the disc prolapse is measured at 11.54 mm. Note also the increased compression of the right S1 nerve root and thecal sac.
Fig. 8 – Change in lumbar spine central canal dimensions. Elderly female patient with a history of neurogenic claudication. (a) Sagittal T1-weighted spin-echo sequence without axial loading. A moderate degree of central stenosis is demonstrated at the L2/3 level but cerebrospinal fluid (CSF) is still identified ventral to the cauda equina. (b) Sagittal T1-weighted spin-echo sequence with axial loading. Critical stenosis has developed at L2/3, mainly due to posterior impression on the theca from the fat pad. (c) Axial T2-weighted fast spin-echo sequence without axial loading. Plentiful CSF is seen ventral to the cauda equina. (d) Axial T2-weighted spin-echo sequence with axial loading. There is now complete loss of CSF around the cauda equina, indicating the presence of occult central canal stenosis.
EFFECT OF LOADING ON THE SYMPTOMATIC/DEGENERATE LUMBAR SPINE

Changes in Disc Morphology

As mentioned previously, Zamani et al. [8] demonstrated an

Fig. 9 – Change in lumbar spine lateral recess dimensions. (a) Axial T2-weighted fast spin-echo sequence without axial loading. (b) Axial T2-weighted spin-echo sequence with axial loading. A marked reduction in lateral recess anteroposterior dimension is demonstrated.

Fig. 10 – Development of occult facet ganglion. (a) Axial T2-weighted fast spin-echo sequence without axial loading. Fluid is seen in the left L4/5 facet joint. (b) Axial T1-weighted spin-echo sequence with axial loading. A small facet ganglion has developed deep to the ligamentum flavum and is contributing to the central stenosis.
increase in disc bulge in 40% of degenerate lumbar discs when imaged in the erect–extended position. Increase in the grading of disc herniation has been reported in six of 76 imaged disc levels between supine and erect–extended position MRI [11]. Axial-loaded MRI has been reported to increase the size of disc herniations in four of 19 patients (Fig. 7) [17]. However, Choy [24] identified that imaging the lumbar spine in compression resulted in accentuation of disc herniation in 50% of patients, as well as reproducing symptoms at the time of imaging.

**Changes in Canal Dimensions**

Sagittal lumbar canal dimensions between erect–flexed and erect-extended MRI have been correlated with sagittal canal dimensions at erect flexion–extension myelography [9]. A high correlation has been demonstrated between the MRI and myelography measurements with a small, but statistically significant, positional dependence on measurements, canal dimensions being least in the erect–extended position, as expected. The same authors found significant positional changes in foraminal dimensions to be uncommon. Possibly of more relevance is the identification of changes in the relationship of the disc margin to the adjacent nerve root with changes in body position. This was investigated by Weishaupt et al. [11], who looked at the effect of supine, erect–flexed and erect–extended MRI on nerve root contact, displacement and compression in 30 patients with chronic low back or leg pain. Nerve root contact with disc was most commonly seen in the erect–flexed position, whereas the incidence of nerve root deviation increased in the erect–extended position. Actual nerve root compression only developed in a single case.

The effect on the lumbar spine of axial compression has concentrated on the assessment of changes in DCSA [13, 14, 17]. Willen et al. [17] assessed the effects of axial compression in three patient groups, those with chronic low back pain, neurogenic claudication or sciatica. They determined the additional valuable information (AVI) obtained on compression studies. This was defined as a greater than 15 mm² reduction in DCSA to levels below 75 mm² (the borderline DCSA, below which spinal stenosis is considered to be present based on intradural pressure measurements), accentuation of disc herniation, lateral recess or foraminal stenosis or the development of an intraspinal synovial cyst. AVI was obtained in 69% of patients with neurogenic claudication (Fig. 8), 14% of patients with sciatica but none of the patients with purely low back pain. However, the latter finding is not surprising as the criteria assessed are more related to nerve root compression rather than features that may be associated with back pain. The percentage of cases with claudication or sciatica in which AVI was obtained increases if only patients with a relative degree of stenosis are included (this being a DCSA below 130 mm²). Accentuation of lateral recess stenosis (Fig. 9), with associated unilateral or bilateral nerve root compression was seen at 42 sites in 35 patients, whereas an occult synovial cyst (Fig. 10) was demonstrated in a single case. The cause of reduced central and lateral recess dimensions is related to changes in the morphology of the posterior disc margin (Fig. 11), increase in thickness of the ligamentum flavum (Fig. 12) and also changes in shape of the posterior epidural fat pad, which actually

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**Fig. 11** – Accentuation of degenerate disc bulges. (a) Sagittal T2-weighted fast spin-echo sequence without axial loading. The L3/4, L4/5 and L5/S1 discs are degenerate with a mild disc bulges at all three levels. (b) Sagittal T2-weighted fast spin-echo sequence with axial loading. The anteroposterior disc measurements have increased at all three levels. Note also development of minor retrolisthesis at L3/4.
Fig. 12 – Increase in thickness of the ligamentum flavum. (a) Axial T2-weighted fast spin-echo sequence without axial loading. The thickness of the right and left ligamentum flavum is measured at 3.83 and 4.06 mm, respectively. (b) Axial T2-weighted spin-echo sequence with axial loading. The thickness of the right and left ligamentum flavum increases to 5.86 and 7.88 mm, respectively.

Fig. 13 – Changes in morphology of the posterior epidural fat pad. (a) Axial T1-weighted spin-echo sequence without axial loading. The ventral surface of the fat pad is concave. (b) Axial T1-weighted spin-echo sequence with axial loading. The ventral surface of the fat pad is now straight.
develops a flattened or convex ventral surface that can compress the thecal sac (Fig. 13). However, the exact contribution of each of these factors has not been determined. Although the effect of axial compression on the foramen has not been formally studied, our initial experience indicates that occult nerve root compression can be identified (Fig. 14).

CONCLUSIONS

It is clear from the combination of cadaveric and in vivo MRI studies that imaging the lumbar spine in the erect–extension position, or with axial compression can identify occult nerve root compression not identified on conventional supine imaging. Although such techniques may increase the sensitivity of MRI for identification of lumbar nerve root compression, further studies are required to determine the effect on specificity, before the true management value of the techniques can be determined.

REFERENCES


Fig. 14 – Dynamic foraminal stenosis. Elderly man with right L5 root symptoms only on standing. (a) Sagittal T1-weighted spin-echo sequence through the right L5/S1 intervertebral foramen without axial loading. Fat is seen inferior and posterior to the exiting L5 nerve root, which is not compressed. (b) Sagittal T1-weighted spin-echo sequence through the right L5/S1 intervertebral foramen with axial loading. Fat has been effaced posterior to the L5 nerve root, which is now compressed, with flattening of its inferior margin.


