Investigating Cervical Foraminal Stenosis Using Imaging Techniques

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DECLARATIONS

The candidate confirms that the work submitted is their own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work have been explicitly indicated. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

The following joint publications have been written as a direct result of the work in this thesis:

1. **Meacock, J**., Schramm, M., Selvanathan, S., Currie, S., Stocken, D., Jayne, D. and Thomson, S. 2021. Systematic review of radiological cervical foraminal grading systems. *Neuroradiology*. **63**(3), pp.305–316.

My contribution: I conceived the systematic review and led the design of the study. I developed the search strategy with support from the University of Leeds Health Sciences Librarian and conducted all database searches. I performed the title and abstract screening, full-text review and extracted data from all included studies. I carried out the analysis and synthesis, produced all tables, figures and the PRISMA flow diagram and wrote the full manuscript. I coordinated contributions from all co-authors, integrated revisions and managed the submission process including responses to peer review.

Contribution from other authors: Schramm acted as the independent second reviewer, providing secondary checks of screening decisions and data extraction. Selvanathan, Currie, Stocken, Jayne and Thomson were my supervisory team and provided oversight, guidance and revision of the manuscript. All authors reviewed and approved the final manuscript prior to submission.

2. **Meacock, J**., Smedley, A., Sinha, P., Igra, M., Macmullen-Price, J., Jayne, D., Stocken, D., Currie, S. and Thomson, S. 2023. Consistency of Radiological Grading of Cervical Foraminal Stenosis. *Current Medical Imaging*, **20**.

My contribution: I conceived the study, designed the methodology and led all stages of the project. I identified and assembled the surgical cohort, extracted clinical and imaging data, performed MRI measurements used for inter-rater and intra-rater analysis and prepared the dataset for analysis. I selected and prepared the MRI studies for review, coordinated the rater training process and oversaw the measurement protocol. I conducted data cleaning, analysis, interpretation and produced all tables, figures and diagrams. I drafted the full manuscript, coordinated revisions from co-authors and managed the submission and peer-review process.

Contribution from other authors: Smedley, Sinha, Igra, Macmullen-Price and Thomson contributed by performing MRI measurements used for inter-rater and intra-rater analysis. Stocken, Jayne, Currie and Thomson were my supervisory team and provided oversight, guidance and revision of the manuscript. All authors reviewed and approved the final manuscript prior to submission.

3. **Meacock, J**., Smedley, A., Sinha, P., Igra, M., Macmullen-Price, J., Jayne, D., Stocken, D., Currie, S. and Thomson, S. 2024. Radiological cervical foraminal stenosis severity and morphology as a predictor of pre-operative function and functional surgical outcome. *British Journal of Neurosurgery,* pp.1–9.

My contribution: I conceived the study, designed the methodology and led all stages of the project. I identified and assembled the surgical cohort, extracted clinical and imaging data, performed MRI measurements used for inter-rater and intra-rater analysis and prepared the dataset for analysis. I selected and prepared the MRI studies for review, coordinated the rater training process and oversaw the measurement protocol. I conducted data cleaning, analysis, interpretation and produced all tables, figures and diagrams. I drafted the full manuscript, coordinated revisions from co-authors and managed the submission and peer-review process.

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The following presentations have been completed due to work in close relation to this thesis:

1. **Meacock, J**., Thomson, S. and Derham, C. 2018. Is length of stay (LOS) equivalent for elective anterior cervical discectomy (ACD) patients in an NHS hospital and as waiting list initiative cases in a private hospital? The Society of British Neurological Surgeons. London.

2. **Meacock, J**., Thomson, S. and Derham, C. 2019. Patient selection leads to a significantly shorter stay in hospital for elective Anterior Cervical Discectomy (ACD) patients as waiting list initiative cases in a private hospital compared to those in an NHS hospital. The Society of British Neurological Surgeons. Manchester.

3. **Meacock, J**., Currie, S., Stocken, D., Jayne, D. and Thomson, S. 2019. Neuroforaminal stenosis using imaging techniques. Society of Academic and Research Surgery (SARS) Annual Meeting. Dublin.

4. **Meacock, J**., Schramm, M., Selvanathan, S., Currie, S., Stocken, D., Jayne, D. and Thomson, S. 2021. Systematic Review of Radiological Cervical Foraminal Grading Systems. American Society of Neuroradiology. Online.

5. **Meacock, J**., Currie, S., Stocken, D., Jayne, D. and Thomson, S. 2021. Investigating neuroforaminal stenosis using imaging techniques. Surgical research society. Online.

6. **Meacock, J**., Currie, S., Stocken, D., Jayne, D. and Thomson, S. 2021. Systematic review of radiological grading systems for cervical foraminal stenosis. The Society of British Neurological Surgeons Virtual Meeting. Online.

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ABSTRACT

Background

Cervical foraminal stenosis is a common cause of radiculopathy, but its radiological assessment remains inconsistent. Multiple grading systems have been proposed and this thesis aimed to evaluate the existing systems, assess their consistency and determine whether radiological severity or morphology predicts functional outcomes after surgery. It also explored the potential role of diffusion tensor imaging in quantifying cervical nerve microstructure.

Methods

A published systematic review identified and appraised 59 published grading systems for cervical foraminal stenosis. A published retrospective cohort study analysed pre-operative magnetic resonance imaging of 50 surgical patients, with six independent raters applying Kim and modified Kim methods to assess inter-rater and intra-rater reliability. A subsequent published retrospective study correlated radiological features with pre-operative and post-operative neck disability index scores following anterior cervical discectomy or posterior cervical foraminotomy. An unpublished prospective diffusion tensor imaging pilot study then investigated diffusion metrics of the cervical nerve roots in relation to pre-operative and post-operative neck disability index scores.

Results

The systematic review highlighted wide methodological variation and limited clinical validation of existing grading systems. Inter-rater agreement for Kim (κ=0.01) and modified Kim (κ=0.08) was poor, though intra-rater reliability was good (κ=0.69–0.81). There was no significant correlation between radiological grades or morphological features and pre-operative or post-operative neck disability index. Surgery significantly improved mean neck disability index but outcomes did not differ between anterior cervical discectomy and posterior cervical foraminotomy. The diffusion tensor imaging pilot demonstrated quantitative assessment of the cervical nerve roots was technically feasible.

Conclusions

Current radiological grading systems for cervical foraminal stenosis demonstrate poor inter-rater reliability and lack predictive value for surgical outcomes. While surgery improved NDI, the existing magnetic resonance imaging-based grading systems used in isolation cannot determine prognosis or surgical approach. Future research should explore 3D imaging and diffusion tensor imaging to provide quantitative measures of nerve integrity that may enhance diagnostic precision, prognostication and personalised surgical decision-making.

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ABBREVIATIONS

ACD	Anterior Cervical Discectomy
ACDF	Anterior Cervical Discectomy and Fusion
ANOVA	Analysis of Variance
AP	Anterior Posterior
ASA	American Society of Anaesthesiology
C	Cervical
CI	Confidence Interval
COPD	Chronic Obstructive Pulmonary Disease
CSA	Cross Sectional Area
CT	Computed Tomography
DICOM	Digital Imaging and Communications in Medicine
DTI	Diffusion Tensor Imaging
DWI	Diffusion Weighted Imaging
FA	Fractional Anisotropy
FOV	Field of View
HRA	Heath and Research Authority
ISO	Isotropic Value
IVDU	Intravenous Drug User
JOA	Japanese orthopaedic association
mJOA	Modified Japanese orthopaedic association
kg	Kilogram
L	Lumbar
MCID	Minimal Clinically Important Difference
MD	Mean Diffusivity
mKim	Modified Kim Grading System
MRI	Magnetic Resonance Imaging
mSv	Millisieverts
NDI	Neck Disability Index
NHS	National Health Service
NMR	Nuclear Magnetic Resonance
PCF	Posterior Cervical Foraminotomy
PEEK	Polyetheretherketone

QA	Quantitative Anisotropy
RDI	Restricted Diffusion Imaging
ROI	Region of Interest
SC	Spinal Cord
SD	Standard Deviation
T	Tesla
T1	T1-Weighted MRI Sequence
T2	T2-Weighted MRI Sequence
TE	Echo Time
TR	Repetition Time
VB	Vertebral Body

1 Introduction

1.1 Background of cervical degenerative disease

Cervical degenerative disease, or cervical spondylosis, is a condition that is characterised by the progressive degeneration of the neck's intervertebral discs, vertebrae, and joints. This degeneration primarily results from the natural aging process, where years of wear and tear lead to the breakdown of these spinal components. However, several other factors can accelerate or contribute to the development of this condition. Genetic predisposition plays a role where individuals with a family history of cervical spondylosis are at a higher risk. Repetitive stress or strain on the neck from activities such as certain sports, jobs that require prolonged periods of sitting or neck movement and other physically demanding tasks can also accelerate the degenerative process. Lifestyle choices significantly impact the progression and severity of cervical degenerative disease (Yang et al., 2015). Smoking, for instance, reduces blood flow to the discs in the spine, impairing their ability to repair and maintain themselves. Obesity increases the physical load on the spine, accelerating wear and tear, while a sedentary lifestyle leads to weaker muscles that are less capable of supporting the neck and spine (Luime et al., 2004). The symptoms of cervical degenerative disease can vary widely among individuals. Commonly, patients experience chronic neck pain, which can be persistent or episodic and neck stiffness, leading to reduced flexibility and difficulty in movement (Rao, 2002; Guzman et al., 2014).

Nerve compression due to degenerative changes can cause brachialgia, presenting with numbness, tingling, and a pins-and-needles sensation in the shoulders, arms, and hands. In some cases, patients may also experience muscle weakness in these areas, affecting their ability to perform daily tasks (Radhakrishnan et al., 1994; Hoy et al., 2010).

Diagnosing cervical degenerative disease typically involves a comprehensive approach. Initially, a detailed medical history and physical examination are conducted to assess the patient's symptoms, neck mobility and any neurological deficits. Imaging tests such as X-rays, MRI (Magnetic Resonance Imaging), or CT (Computed Tomography) scans, are crucial in visualising the extent of degeneration, identifying specific areas of disc damage, bone spurs, or spinal cord compression, and ruling out other conditions that may present with similar symptoms. Nerve conduction studies may be used to evaluate nerve function and detect any nerve damage or muscle impairment caused by the degenerative process (Binder, 2007; McCartney et al., 2018).

Treatment for cervical degenerative disease is tailored to the severity of the condition and the specific symptoms experienced by the patient. Conservative treatments are often the first line of management. Analgesia can help manage pain and inflammation. Physiotherapy is highly beneficial, focusing on exercises that improve neck flexibility, strength and posture. Lifestyle modifications play a crucial role in managing the disease. Ergonomic adjustments, such as proper workplace setup and good posture, weight management, and smoking cessation, are essential preventive and therapeutic measures (Evans et al., 2002; Haines et al., 2008). When conservative treatments are insufficient, interventional procedures may be considered. Cervical nerve injections can reduce inflammation and alleviate pain by delivering steroids or anaesthetic agents directly to the affected area around the spinal cord. This can provide temporary relief by interrupting pain signals. In severe cases where there is significant nerve compression, surgical options may be necessary (Botwin et al., 2003; Levin, 2009; Wong et al., 2014).

The prognosis for cervical degenerative disease varies widely among individuals. While many people can manage their symptoms effectively with conservative treatments and lifestyle changes, others may require surgical intervention to achieve significant relief. Prevention strategies are essential to mitigate the risk of developing or worsening the condition. Maintaining good posture, especially during activities like sitting, working on a computer, and sleeping, is crucial. Regular exercise that strengthens the neck and back muscles, along with healthy lifestyle choices such as a balanced diet, avoiding smoking, and managing weight, can help slow the progression of cervical degenerative disease and improve overall spine health (Sheng et al., 2017; Chen et al., 2018). To understand the symptoms and signs generated from cervical spondylosis and the various treatment stratifications it is essential to first consider the anatomy of the spine, particularly the cervical spine and moreover the neural exit foramina, the holes through which the spinal nerves pass.

1.2 Anatomy of the spine

The spine or vertebral column is divided into bony segments consisting of vertebrae and intervertebral discs. The skull, both scapulae, the pelvic girdle and ribs connect to this to create a bony framework to which soft tissues and muscles can attach. There are 33 vertebrae in total that are divided into five groups due to their location in the spine and their morphology, from cranial to caudal: Cervical, Thoracic, Lumbar, Sacral and Coccygeal. Intervertebral discs separate each vertebra and comprise a central nucleus pulposus with an outer ring of anulus fibrosis. The annulus fibrosis consists of several alternating obliquities of collagen fascicles in adjacent laminae. In the cervical region there are seven vertebrae. These vertebrae are small when compared with others and they are distinctive with respect to a foramen in their transverse process. There are 12 thoracic vertebrae which are unique due to their rib articulation. The five lumbar vertebrae with notable large size aid load bearing and skeletal support. The five sacral vertebrae are normally fused and articulate with the pelvic bones. Finally, the coccyx formed commonly of three to five vertebrae (Gray et al., 2005).

A typical vertebra consists of a ventral body and dorsal vertebral arch surrounding the vertebral canal (Figure 1-1). The canal contains the spinal nerve roots, spinal cord, meninges and associated vasculature. The bodies ventrally form a column and are connected by intervertebral discs as well as the anterior and posterior longitudinal ligaments. The vertebral arch dorsally consists of three main components; the pedicles attach the vertebral body to the lateral masses; the laminae connect the lateral masses to the spinous process; the transverse process projects laterally from the lateral mass. The spinous process projects in the midline in a dorsal and inferior direction. The transverse and spinous processes provide the main attachments for muscles and the interspinous ligaments. The lateral mass consists of the pars interarticularis between paired superior and inferior articular processes that make the facet joints. The ligamentum flavum closes the gap between the laminae and prevents separation of the laminae in spinal flexion. In adults the normal curvatures of the spine include the cervical lordosis, thoracic kyphosis and a lumbar lordosis (Gray et al., 2005).

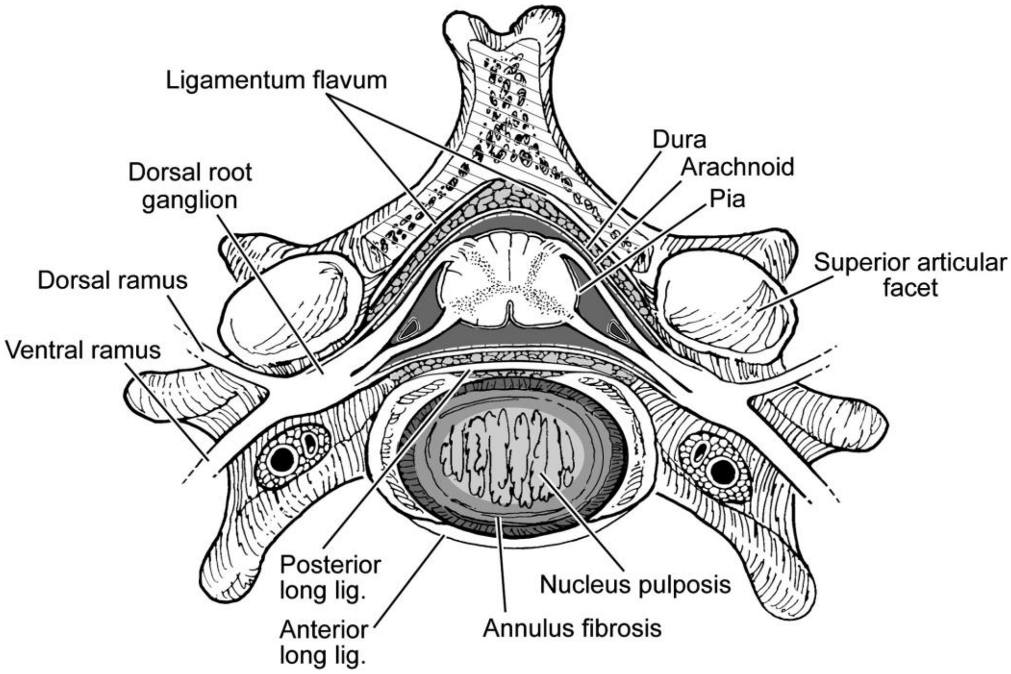


Figure 1-1 Diagram of nerve exiting the foramen
Image adapted from (Polston, 2007)

1.2.1 Anatomy of the cervical spine

The atlas supports the skull and articulates with the axis, whose odontoid process permits axial rotation. The remaining cervical vertebrae are relatively small and increase in size caudally, with triangular vertebral foramina adapted to accommodate the cervical spinal cord. The sub-axial cervical vertebrae are broadly similar, although C7 has a longer spinous process. Each spinal level has a corresponding nerve, with the additional C8 nerve exiting between C7 and T1. Nerve roots from C1 to C7 exit above their corresponding pedicle, whereas C8 exits below C7 (Figure 1-2). Cervical nerves are formed by union of the ventral (motor) and dorsal (sensory) roots, the latter containing the dorsal root ganglion. These roots merge in the intervertebral foramen to form a mixed spinal nerve, which exits through the neuroforamen before dividing into dorsal and ventral rami. The dorsal ramus supplies the muscles and skin of the posterior neck and trunk, while the ventral ramus supplies the anterior and lateral neck and contributes to innervation of the upper limb (Childress, 2016).

The anterior rami of the cervical nerves C1 to C4 form the cervical plexus, which innervate the muscles and skin of the neck and shoulder. The anterior rami of the cervical nerves C5 to C8, along with the first thoracic nerve (T1), contribute to the brachial plexus, a complex network that innervates the shoulder, arm, and hand. From these plexuses, the nerves branch out into specific peripheral nerves that target distinct muscles and dermatomes (Figure 1-3). For example, nerves such as the median, ulnar, and radial nerves extend from the brachial plexus into the arm and hand, providing motor control, autonomic and sensory feedback. This intricate network ensures that neural signals are effectively transmitted between the central nervous system and peripheral targets (Childress, 2016).

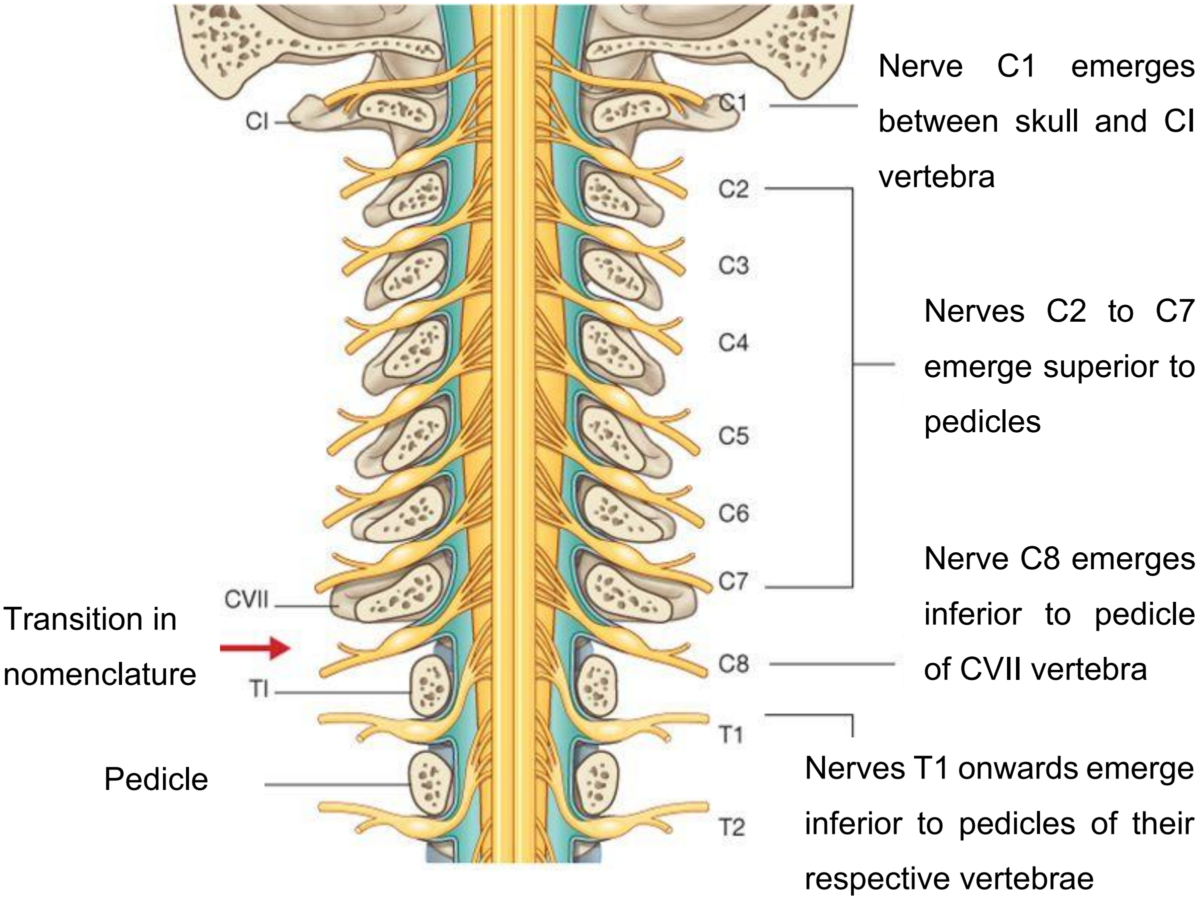


Figure 1-2 Image depicting the exiting nerves from the cervical spine
Image adapted from Gray's Anatomy (2005)

The cervical nerves are supported and protected throughout their pathway by various anatomical structures. The intervertebral discs act as shock absorbers, while the facet joints facilitate movement and provide stability. Ligaments and surrounding musculature, such as the scalene and sternocleidomastoid muscles, offer additional support and protection, ensuring that the nerves can function without undue compression or injury. The vertebral arteries, ascending through the transverse foramina of the cervical vertebrae (except for C7), are critical as they supply blood to the brain, nerve roots and spinal cord. Pathological conditions affecting the cervical spine, such as trauma or degenerative changes, can compromise these arteries, potentially leading to reduced cerebral blood flow and serious neurological sequelae (Gray et al., 2005; Childress, 2016; Wang et al., 2016).

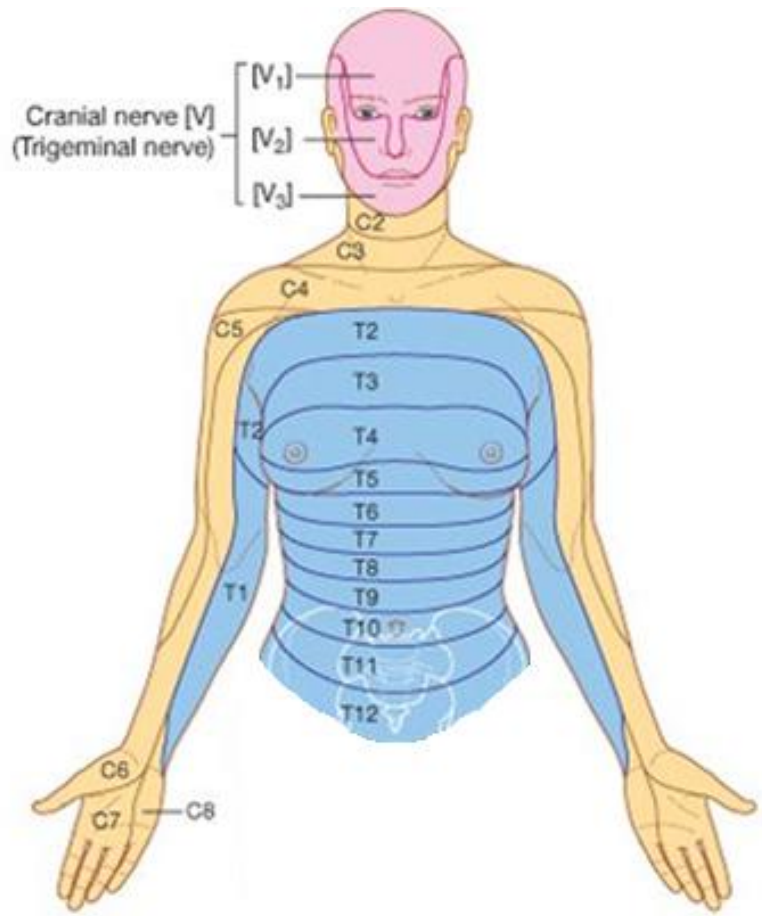


Figure 1-3 Dermatomal map of the upper limbs of the human body
Image adapted from Gray's Anatomy (2005)

1.2.1.1 Cervical neuroforamina

The anterior margin of the neuroforamina is the posterolateral aspect of the superior vertebral body, the posterolateral aspect of the intervertebral symphysis and the posterolateral part of the body of the inferior vertebra. The cranial margin, comprising the inferior vertebral notch of the vertebra above, is shaped by its pedicles, while the caudal margin is defined by the upper edge of the pedicle below. The posterior border is created by the ventral aspect of the fibrous capsule of the facet joint (Wang et al., 2016) (Figure 1-4).

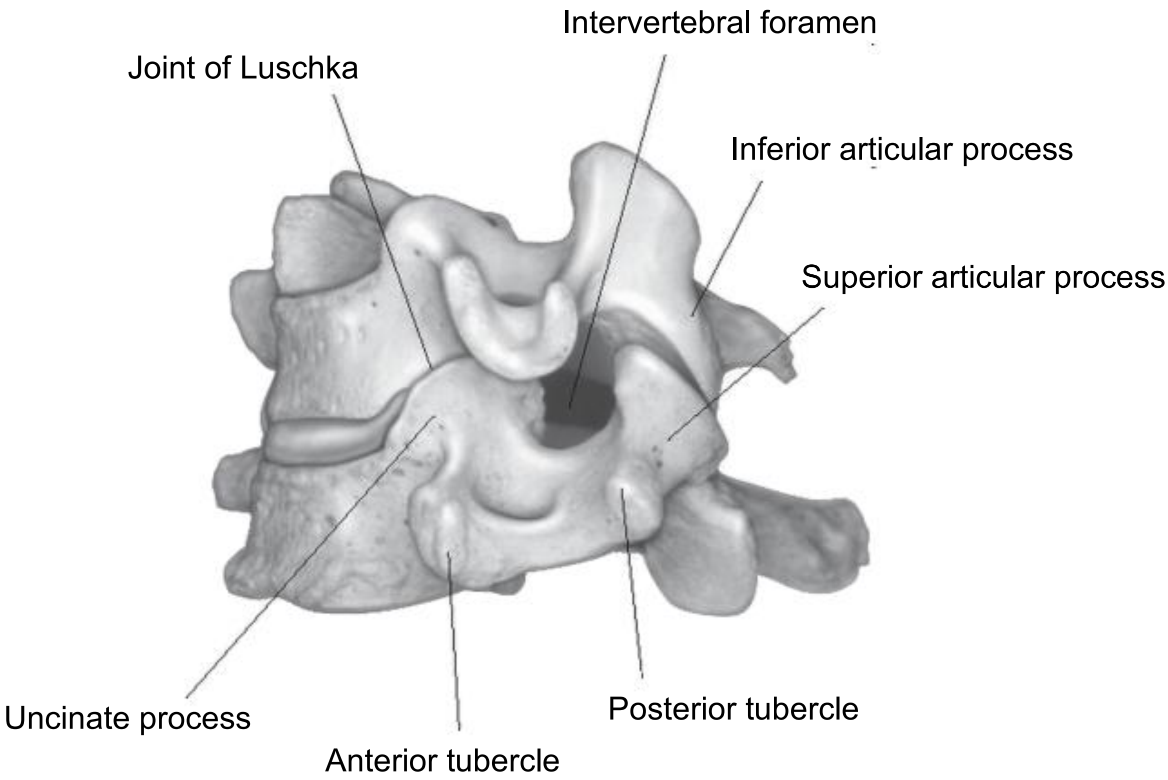


Figure 1-4 Sagittal bony anatomy and borders of the intervertebral foramina Adapted from Louis-ugbo et al., (2016)

Uncinate comes from the Latin uncus meaning hook-shaped, imagine the edges of the C3-C7 vertebral bodies having the hooked/curved margins. Osteophytes normally arise around the disc boundary and uncovertebral region. The uncovertebral joint, also known as Luschka joint, is formed from C3-C7 by the uncinate process on the lateral margin of superior endplate and the opposing surface of the inferior aspect of the vertebral body above. The uncinate processes and bony protrusions extend cranially forming the medial surface of the intervertebral foramen. This enables flexion and extension and reduces lateral flexion and axial rotation (Wang et al., 2016).

The bony foramina are covered by fibrous tissue making the true nerve root canal smaller than the bony dimensions. The contents of the neuroforamina are the segmental mixed spinal nerve, nerve root ganglion, meningeal sheath and meningeal nerves as well as spinal radicular arteries and epidural veins connecting internal and external venous plexuses. It has been commonly described as having 3 distinct zones (Figure 1-5) which are the medial (related to the pedicle), middle (related to the vertebral artery) and lateral zones (Ebraheim et al., 1996).

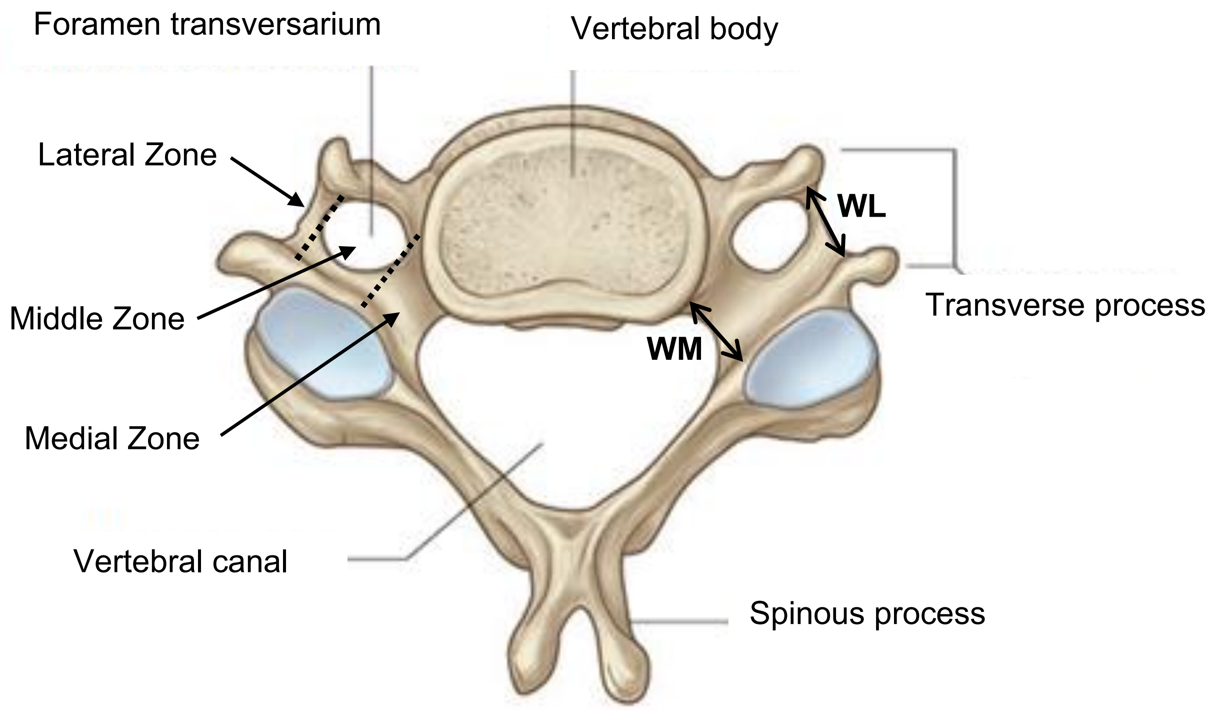


Figure 1-5 Anatomical parameters of the neuroforamina measured from cadaveric models
WM = Medial Zone Width WL = Lateral Zone Width. Image inspired from Ebraheim et al., (1996) but adapted from Gray's Anatomy (2005)

The neural foramen is narrowest in the medial zone and it then widens laterally (Tanaka et al., 2000). It is thought therefore that the medial zone is the most important for patients that have radiculopathy, symptoms arise when the nerves are compressed or pinched. In the sagittal plane the neuroforamina follow an hourglass shape with the superior and inferior foraminal widths being larger than the middle foraminal width (S. Craig Humphreys et al., 1998). The canal forms an angle of approximately 45 degrees to the anteroposterior plane and is inclined downwards by 10-15 degrees from the axial plane (Sohn et al., 2004). The normal neural foramen is complex and has been studied by various teams across the world.

There have been various methods used to investigate and quantify the dimensions of the neuroforamina which include radiological imaging and direct measurements with probes (Yoo et al., 1992) and transducers (Nuckley et al., 2002). Fresh frozen human head and neck cadavers have been utilised as they can be manipulated and scanned without risk to human volunteers. They are stripped of their soft tissues until the bony anatomy, ligaments, facet capsule and discs can be visualised. Studies started to appear in the literature from around the 1980s (Davidson et al., 1981; Modic et al., 1986; Teresi et al., 1987) attempting to better investigate this structure. The foraminal dimensions were measured using a cryomicrotome (an instrument that permits the slicing of tissues into extremely thin sections at very low temperatures). It was found that the dimensions of the cervical neuroforamina were nine millimetres in height, between four and seven millimetres in width and between four and six millimetres in length (Houser et al., 1993; Ebraheim et al., 1996). The shape on entry and exit is wider than the middle zone with an overall trend on increasing size of the neuroforamina cranial to caudal (Jenis et al., 2004). Measured cadaveric foraminal cross sectional areas (CSA) have been reported to range widely dependent on the location measured and due to the hourglass shape (Sohn et al., 2004). Cadaveric studies however are limited in their applicability to the *in vivo* situation due to the lack of normal loading, absence of soft tissues and different biomechanics (Anderst, 2012). There can be problems using cadaveric models to measure the neuroforamina as varying degrees of soft tissue dissection is performed which may not represent the *in vivo* situation and if the spine is without its full constituents such as the skull there will be abnormal loading and therefore the dimensions of the neuroforamina will be changed. Cadaveric studies, while invaluable for detailed anatomical insights into the cervical neuroforamina, come with several significant disadvantages that limit their application in replicating living conditions and dynamic processes. A major limitation is the lack of physiological processes in cadavers, meaning that critical factors such as blood flow, inflammation, and healing cannot be observed and these processes are essential for understanding how the different anatomical elements influence neuroforaminal morphology. Post-mortem changes in tissues also pose another problem, as decomposition can alter anatomical structures, potentially leading to inaccurate representations of living anatomy and pathology. Additionally, cadaveric studies are inherently static, which means that dynamic processes such as spinal flexion, lateral bending and extension, with their corresponding effects on the neuroforamina, cannot be studied effectively. Finally cadaveric studies cannot demonstrate the progression of diseases or the effectiveness of interventions over time. They offer only a single snapshot, whereas many spinal conditions are dynamic and evolve. This static nature means that cadaveric studies cannot provide insights into how degenerative diseases develop or respond to treatments over extended periods (Anderst, 2012).

These limitations highlight the need for complementary approaches, such as advanced imaging techniques and *in vivo* studies, to obtain a more comprehensive understanding of cervical neuroforaminal pathologies and what their implications are in living patients.

1.2.1.1.1 Movements of the cervical spine

The dimensions of the cervical neuroforamina change significantly as the cervical spine moves through its full range of motion. It can normally rotate about its axis 70 degrees, flex 45 degrees, extend 55 degrees and laterally flex to 40 degrees as illustrated in Figure 1.6.

During flexion and extension, the calibre of the neuroforamina changes significantly. The neuroforamen is smallest during extension and enlarges with flexion as demonstrated using blunt probes in cadaveric specimens (Yoo et al., 1992). It has also been demonstrated using plain film radiographs in cadaveric models that extension of the cervical spine leads to maximal reduction in dimensions of the C4/C5 neuroforamina compared with other levels. The C5 nerve has therefore been theorised to be at the highest risk of compression (Panjabi et al., 2006; Guzman et al., 2014). Cadaveric models allow manipulation of the cervical spine and reproducible changes in the neuroforaminal dimensions which can be closely controlled. An increase in thoracic kyphosis has been shown to cause a corresponding reduction in the dimensions of the cervical neuroforamina due to compensatory cervical extensions (Smith et al., 2016).

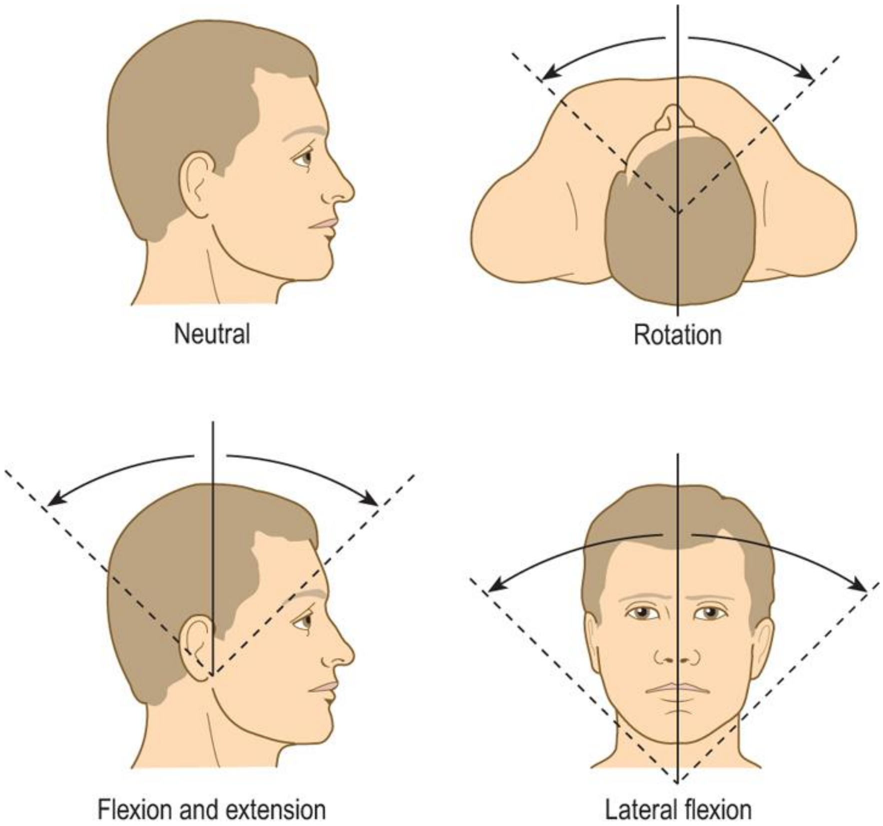


Figure 1-6 Movements of the cervical spine
Image adapted from Gray et al., (2005)

In a healthy volunteer study into the changes of the cervical neuroforamina MRI was used to quantify the CSA during flexion and extension. It was found that flexion led to an increase in the neuroforamina by 30 percent and extension caused a reduction by 19 percent from the neutral position (Muhle et al., 2001). A similar study was performed using oblique CT images measuring height, width and CSA, where flexion caused an increase in area of 28 percent and extension a decrease of between 17 and 22 percent from the neutral position (Kitagawa et al., 2004). When axial rotation is compared with extension it was found that the dimensions of the neuroforamina are smallest in extension (Y. Yeni et al., 2016).

Distraction forces and their effects on the neuroforamina CSA have been investigated using MRI. When increasing axial distraction force are applied, symptoms have been shown to improve though increasing the distraction force above 15kg can induce neck pain. An axial force of 12kg was found to increase the neuroforaminal CSA by 20% and a compressive force of seven kilograms decreased it by 30% (Takasaki et al., 2009). Cervical traction temporarily enlarges the neural foramen and may provide short-term symptom relief, but there is no strong evidence that these structural changes persist once traction is removed (Liu et al., 2008). The long-term benefits of traction are unclear, most studies are of low quality and as a result, it is no longer widely used in clinical practice. Exercise-based and manual therapies offer more consistent, evidence-based outcomes and are easier to deliver safely and effectively (Abi-Aad and Derian, 2025).

1.3 Pathology of cervical degenerative disease

Cervical degenerative disease (cervical spondylosis) occurs commonly as patients age. There are three main joints at each level of the cervical spine the two posterior joints and the disc. These undergo degenerative changes which lead to instability, compression of surrounding structures and deformities of the spine (Sohn et al., 2004). Deformities of the spine are commonplace in patients with degenerative spine disease. It affects the intervertebral discs, vertebral bodies, facet joints and ligaments of the spine. The frequency of degeneration of the cervical spine increases with age. It has been shown through MRI investigations that degenerative changes are present in 17% of men and 12% of women in their twenties which then rises to 86% and 89% respectively over the age of sixty. The most commonly affected level is C5/C6 in imaging studies (Matsumoto et al., 1998) in contrast to cadaveric studies demonstrating C4/C5 as the most affected level. At birth the healthy nucleus pulposus proteoglycan matrix contains 70-90% water. With age comes disc dehydration which leads to loss of disc height and a move towards opposing endplates becoming closer together. This is exacerbated by the discs being avascular and being dependent on the vertebral endplates for their oxygen and nutrients. Loss in disc space height occurs until the vertebral bodies encounter one another, and osteophyte formation begins to occur. Secondary issues from this loss of height can be compression of neural and vascular structures leading to motor and sensory symptoms (Ferrara, 2012).

The causes of nerve root compression include osteophytes, ligamentous hypertrophy, intervertebral disc herniation and/or a combination of all factors which are a result of the aging process.

Osteophyte formation represents a key feature of cervical spondylotic change. These bony projections develop initially through cartilaginous proliferation, forming a cartilaginous cap that subsequently undergoes ossification from its base. This process progresses until a mature bony spur remains, typically covered by a thin layer of fibrocartilage (Sabiston et al., 1987). In the normal cervical spine, approximately 70% of axial load is transmitted through the anterior (ventral) column and 30% through the posterior (dorsal) elements. However, the development of osteophytes alters this load distribution, shifting stress towards the uncovertebral joints and uncinate processes, thereby contributing to further degenerative change (Sohn et al., 2004).

Changes in the shape of the ligamentum flavum and facet joint capsule can also contribute to posterior impingement of the neuroforamina. These alterations are driven by a reduction in disc height, which causes the supporting ligaments to lose tension and buckle. Repetitive bending, flexion and mechanical stress further exacerbate this collapse, promoting progressive shift of the cervical spine from its normal lordotic curve toward a kyphotic alignment (Rao, 2002). Both the posterior longitudinal ligament and ligamentum flavum may thicken over time. In the case of the posterior longitudinal ligament, this thickening often represents reactive hyperplasia of fibrocartilage, capillaries and connective tissue as a response to chronic pressure from adjacent material, which tends to occur before ossification develops. Ligamentum flavum can be at higher risk of hypertrophy through genetic predisposition (Ferrara, 2012).

Discs over time become less hydrated and more fibrous with a reduction in proteoglycans, increasing stiffness and propensity for damage (Gray et al., 2005). This loss of hydration is due to a change in the composition, an increase in the ratio of keratin sulphate to chondroitin sulphate. The discs become inelastic, reduce in height and their weight bearing capacity is diminished. The dorsal portion of the annulus fibrosis is weaker than the ventral aspect which leads to the nucleus pulposus more commonly herniating ventrally. These herniated discs have been shown to have granulation tissue within them, increased vascularisation and permeation of macrophages when compared with healthy discs. Disc herniation may be central but is more commonly lateral because the posterior longitudinal ligament is weaker laterally. This is more common in younger people, may be associated with trauma and is more likely to improve with conservative management. It is responsible for only a small proportion of the patients presenting with cervical radiculopathy that have failed to respond to conservative management (Ferrara, 2012).

1.3.1 Individual and environmental risk factors

Although cervical degeneration is largely spontaneous, genetic susceptibility and environmental factors can accelerate its progression (Rao, 2002; Guzman et al., 2014). Only 15% of cases of cervical radiculopathy are preceded by trauma (Radhakrishnan et al., 1994). Increasing age, sedentary lifestyle, smoking, obesity, poor sleep and genetic factors all appear to increase risk. Smoking impairs disc nutrition and repair, while inactivity contributes through muscle weakness, poor posture, reduced disc hydration and joint stiffness. Obesity adds further mechanical, inflammatory and metabolic stress to the cervical spine (Luime et al., 2004). Occupational risk appears highest in the military, entertainment industry, healthcare support, and maintenance and repair work because of repetitive movement, awkward posture, lifting and trauma exposure. Psychosocial stress and poor ergonomics may also contribute. Addressing these factors through ergonomic improvements, injury prevention and occupational health measures may help reduce risk (Yang et al., 2015).

1.4 Symptomatic cervical spondylosis

In the general population between 14% and 71% will have cervical pain at some point and it is common to have multiple recurrences (Binder, 2007). The annual incidence of cervical pain has been estimated in the United Kingdom as 17.9% (Côté et al., 2004) in comparison to Canada with 10.4% (Ehrmann Feldman et al., 2002) and Finland with 21.3% (Ståhl et al., 2004). The six-month prevalence has been estimated as 33.7% in the United Kingdom and 17.1% in Finland with a point prevalence of 22.7% in Canada (Côté et al., 1998). The average age at onset of neurological symptoms is 49 years old with a range of between 14-70, 75% are aged between 40 and 59 years old (Lees and Turner, 1963).

The clinical history obtained from the patient is very important and there are a collection of red flag symptoms that must be considered; if the patient has sustained a fall or any trauma which might have led to a fracture, if they have had any unexpected weight loss or a previous cancer making a diagnosis of neoplasia more likely, if there is fever or a history of night sweats or lymphadenopathy which raises the possibility of an infective cause or if there is evidence for a progressive neurological deficit (Binder, 2007). In the absence of these red flag symptoms, most cervical complaints can be categorised into three syndromes which are axial neck pain, cervical spondylotic myelopathy and cervical spondylotic radiculopathy (Montgomery and Brower, 1992). People can have overlapping symptoms of all three syndromes or at the other extreme may just have incidental changes that have been found accidentally on imaging.

Symptoms can develop acutely (less than one month), sub-acutely (one to three months) or chronically (greater than three months). The time course of symptoms is helpful to exclude spinal malignancies, vascular events or infections.

1.4.1 Axial neck pain

Axial neck pain is benign and self-limiting for the most part. The only noticeable abnormality for some patients may be a decrease in the range of movement of their cervical spine, however there is usually a great deal of movement preserved. Commonly there is localised tenderness over the muscles. Cervicalgia refers to pain originating in the neck and is commonly seen in patients without additional neurological features. However, it can be associated with symptoms such as brachialgia (radiating arm pain), as well as sensory disturbances or motor weakness, which may reflect cervical radiculopathy. In some cases, cervicalgia may also occur alongside signs and symptoms of cervical myelopathy, particularly in more advanced disease. It has been shown that 90% of people with just cervicalgia have no identifiable cause. Muscle spasms and stiffness are usually transient but can lead to headaches and pain extending down the back into the lumbar region (Hoy et al., 2010).

1.4.2 Cervical myelopathy

Cervical myelopathy refers to the clinical syndrome caused by dysfunction of the spinal cord, most commonly due to cervical cord compression. In this context, cord compression is the anatomical finding and myelopathy is the neurological consequence, so the terms are closely related but not strictly synonymous (Matsumoto et al., 1998). It can be due to disc herniation or degenerative osteophytes which lead to neurological impairment. Cervical myelopathy is associated with neck and back pain, electric shock symptoms and numbness. It involves a progressive loss of motor function with spasticity and if left untreated can become irreversible (Matsumoto et al., 1998). Patients that have a loss of upper limb function should have myelopathy from central cord compression excluded. Central cord compression is most commonly degenerative and normally causes anterior cord syndrome (loss of pain and temp, preservation of proprioception) or central cord syndrome (upper limb and hand weakness worse than lower limb weakness). Severe central cord syndrome may also be seen with a syrinx or intermedullary tumour causing muscle wasting in the absence of neck pain or brachialgia.

1.4.3 Cervical radiculopathy

The incidence of cervical radiculopathy from the combined pathologies of disc and degenerative disease (osteophytes, narrowed disc space or foramen) is estimated as 58.5 per 100,000 people however this drops to 18.6 per 100,000 for disc herniation alone (Radhakrishnan et al., 1994). It has shown that cervical radiculopathy affects men more frequently than women in a ratio of 3:2 (Magnus and Mesfin, 2019) and is most prevalent after 40 years old (Hoy et al., 2010). Radiculopathy occurs where there is impaired conduction of a spinal nerve with radicular pain being caused by inflammation frequently secondary to compression of the nerve. Radicular symptoms secondary to compression are usually from osteophytic disease or soft disc herniation and are in the dermatomal distribution of that nerve root (Figure 1-3). The compression of the nerve fibres can lead to sensory, motor and autonomic impairment and thus changes in blood flow, vascular permeability and axonal transport which have all been demonstrated in animal models (Hubbard et al., 2008). Pressure from soft disc material can affect the nerve in two ways: it can directly compress the nerve and it can also create tensile (stretching) forces. This occurs because spinal nerves are anchored in place by connective tissues and ligaments, such as the dura and nerve root sleeves, which tether the nerve to surrounding structures. When the disc bulges or herniates, it may not only push on the nerve but may also stretch it indirectly through these attachments, potentially worsening pain and neurological symptoms (Farmer and Wisneski, 1994).

The neuroforamina are passageway through which the nerves travel and they can become compressed at many different locations. It has been shown that 52% of compression is proximal, where the nerve enters, and this most commonly arises from the uncinate process or the posterolateral region of the vertebral body. Approximately 20% of nerve compression occurs within the neuroforamen itself, while the remaining 28% arises at the point where the nerve exits the foramen. This compression most commonly affects the anteromedial aspect of the superior facet joint and the posterolateral region of the uncinate process. Neuroforamina are reduced in size in symptomatic people when compared with those in asymptomatic people (LeVasseur et al., 2021). Degenerative changes can cause the nerve to be forced superiorly or inferiorly into the recess of its hourglass shape reducing the CSA available for the nerve and leading to compression (Houser et al., 1993). Furthermore it has been shown that changes in the neuroforaminal width are more important than height, as width changes more with movement thus leading to greater compression (Chang et al., 2017).

Compression of the nerves as they pass through the neuroforamina is multifactorial. Not only is the location of stenosis but importantly also the type of compression. Symptomatic radiculopathy is caused by around 20 to 25 percent of the time by disc herniation, with the remainder due to osteophytic compression (Carette, 2005; Kim et al., 2016). The symptoms from herniated disc compression can be worse than those from osteophytes, as chemical mediators can cause further nerve irritation (Wong et al., 2014). Symptoms radiate distally down the arm and are commonly in at least one dermatomal distribution pattern (Magnus and Mesfin, 2019). Patients can have mild weakness but rarely have significant disability. Anterior compression occurs most commonly from osteophytes or a soft disc prolapse with posterior compression from facet joint capsule hypertrophy (Sohn et al., 2004).

People can have congenitally narrowed neuroforamina which makes them at a higher risk of nerve root compression (S. Craig Humphreys et al., 1998). The most common location of nerve root impingement by disc herniation is at the medial end of the root canal within the neuroforamina. Anterior compression may involve the ventral (motor) fibres of the exiting spinal nerve, leading to motor weakness. Posterolateral compression from facet joint hypertrophy may affect the nerve root from behind producing sensory symptoms. Most commonly there is a combination of both (Abbed and Coumans, 2007). Cervicalgia and brachialgia are rarely helpful in localising the level of the compression. The dermatomal and myotomal distribution of symptoms and signs is more reliable when identifying the location of the compression of affected nerves.

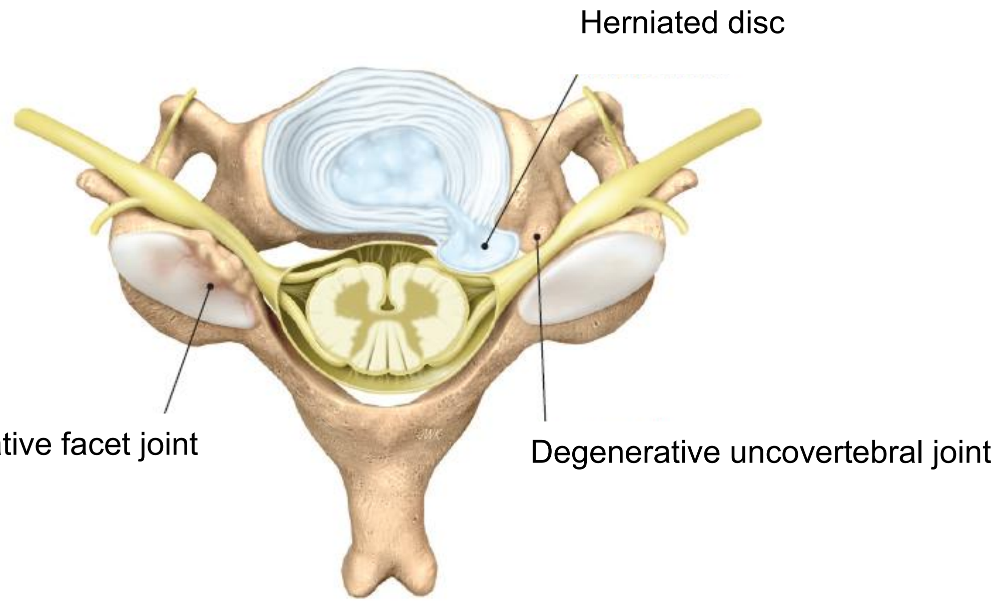


Figure 1-7 Image depicting common causes of nerve root entrapment
Image adapted from Childress (2016)

1.4.4 Alternative differential diagnoses

The most frequent differential diagnoses are the peripheral nerve compression syndromes especially carpal tunnel syndrome, ulnar nerve compression and brachial plexus pathologies. Neural degenerative and inflammatory diseases especially motor neurone disease and peripheral neuropathy must also be considered.

Carpal tunnel syndrome can be differentiated from C6 radiculopathy by the absence of neck pain, normal C6 reflexes, typical nocturnal presentation and if severe, loss of thenar muscle bulk. Ulnar nerve compression may occur at the elbow or very rarely at the wrist. It can be distinguished from C7 radiculopathy by the absence of neck pain, presence of a clawed hand and preservation of the triceps reflex. Brachial plexus pathologies may affect the upper nerve roots (Erb's palsy), lower nerve roots (Klumpke's Palsy) or the entire brachial plexus. These syndromes are usually caused by trauma or pathologies at the lung apex especially a Pancoast tumour. Rarely a cervical rib may cause lower cervical spine or upper thoracic symptoms in young adults and is frequently associated with vascular symptoms. Tightness or hypertrophy of the scalene muscles can compress these nerves, leading to thoracic outlet syndrome, which manifests with symptoms similar to cervical radiculopathy.

Schwannomas and osteochondromas have been known to cause radiculopathy. External compression from malignant tumours of the vertebra or lung apex should also be considered. Weight loss, a history of previous malignancies or fever, intravenous drug use or immunocompromise are important risk factors to consider (McCartney et al., 2018).

1.4.5 Clinical examination findings

During clinical examination positioning of the patient is very important so that individual reflexes can be elicited. Deep tendon reflexes will be diminished on the affected side and must be compared with the unaffected side (Magnus and Mesfin, 2019). There are various special tests that can be performed to elicit or help alleviate the symptoms of cervical nerve root compression by manipulating the anatomy to cause a reduction or expansion of the neuroforamina. Lateral flexion of the neck may provoke symptoms. Spurling's test may induce symptoms in the patient. The Spurling test was first described in 1944 it involves the patient extending and laterally flexing their cervical spine towards the affected side. Pressure on the nerve may provoke symptoms which radiate to the ipsilateral side. Spurling’s test has high specificity but low sensitivity (Thoomes et al., 2018). The shoulder abduction test was first outlined in 1956, ipsilateral shoulder abduction above the head may alleviate symptoms of cervical radiculopathy. It is thought that this manoeuvre leads to less tension on the nerve and therefore can relieve symptoms. This test has also been shown to have high specificity but low sensitivity (Davidson et al., 1981). The neck distraction test involves manual traction by lifting the patient’s head in the supine position, which should lead to alleviation of symptoms. This has also been shown to have high specificity but low sensitivity for patients with symptoms of radiculopathy (Viikari-Juntura et al., 1989). Lhermitte’s sign is where the patient experiences an electric shock like pain radiating down the upper limb following flexion of the neck. It is caused by irritation of the dorsal column fibres however it is neither sensitive or specific for cervical radiculopathy (Teoli et al., 2019). Electromyography is also widely used in patients who have symptoms that are not typical and where there is concern that the neurological changes are more likely to be secondary to an alternative neurological disorder of the upper limb.

The diagnosis of cervical radiculopathy depends on imaging most commonly with MRI or CT myelography where MRI is contraindicated. The clinician needs to correlate the findings on the images obtained with the clinic manifestations to identify pathology that is responsible for the symptoms.

1.5 Management of cervical radiculopathy

Cervical degenerative disease is very common and was found to be present in 86% of asymptomatic patients over the age of 40 when MRI was completed for other reasons (Brinjikji et al., 2015) however, only a small proportion of people with cervical degenerative disease will develop the symptoms of cervical radiculopathy. Those patients that present with symptoms of cervical radiculopathy should be managed in a progressive manner and the condition has a favourable outcome. Although there is a role for surgical intervention there is little evidence that this should be offered in the acute period. It has been shown that 85% of patients presenting with acute symptoms will settle with conservative management in eight to 12 weeks (Guan et al., 2018). A systematic review for disc herniation alone reported that substantial patient improvements occur in four to six months with the time to complete recovery taking between 24 and 36 months (Wong et al., 2014). To help assist the healing process several non-surgical approaches are used first line including physiotherapy, non-steroidal anti-inflammatory drugs and education. For those where symptoms fail to settle, imaging and surgery may be considered.

1.5.1 Conservative management

Cervical radiculopathy in many cases (85%) resolves conservatively. There have been studies performed that have tried to investigate how non-surgical approaches have affected the length of symptoms that a patient suffers. Initially education is important, with formal information delivered to the patient regarding the diagnosis and prognosis expected. Education can be directed at lifestyle modifications that will reduce the likelihood for precipitating causes such as poor posture (Haines et al., 2008). It is common for these patients to want to rest their neck, with no evidence for particular pillows or mattresses (Bernateck et al., 2008), however mobilisation is more effective at increasing the rate at which the patient returns to their normal baseline and collars should not be used (Persson et al., 1997). The patient can use cold sprays, gel packs or other cooling methods to apply to the area which is causing pain. Also heat therapies such as hot packs, saunas and warm baths have been shown to modestly reduce spinal pain (Hurwitz et al., 2002). This is low cost, non-invasive and has negligible risk of complications. It has been suggested that these treatments reduce local inflammation but it is more likely that they operate through an attention distraction mechanism (Grana, 1993).

Exercises have been used to improve patient symptoms. These are normally delivered by a physiotherapist and then continued between interventions by the patient at home (Evans et al., 2002; Gross et al., 2015). Strength resistance training and increased overall physical activity with aerobic exercises such as walking or using a treadmill on level ground (Jull et al., 2002) have been shown to improve pain with between one and three sessions per week for at least four weeks (Andersen et al., 2008).

Patients have shown benefit from using non-steroidal anti-inflammatory medications (NSAIDs) in conjunction with a gastro-protective medication, such as proton pump inhibitors like lansoprazole, to reduce the likelihood of developing stomach ulceration (Graham et al., 2002). NSAIDs are low cost and help to relieve the patient of symptoms (Peloso et al., 2007). Medications such as amitriptyline have been shown to improve pain and quality of sleep for patients that do not have adequate relief with simple analgesia alone (Maizels and McCarberg, 2005).

Mechanical traction is thought to reduce spinal pain by stretching muscles and increasing the dimensions of the neuroforamina and thus the cervical nerve root compression. There are various ways that this can be carried out and manual or mechanical traction are used most frequently. It has been shown that there is little benefit from traction and this method of improving symptoms is rarely used in practice due to its poor evidence base (Graham et al., 2006).

There is very little evidence that oral glucocorticoids are effective in reducing symptoms for patients with cervical radiculopathy. They are associated with many adverse side effects such as poor glycaemic control, osteoporosis, hypertension and increased infection risk (Finckh et al., 2006). Cervical nerve root injections (Levin, 2009) have been used and although it has been shown that they can offer relief of symptoms for a short period of time the risks such as cerebrospinal fluid leak, meningitis and nerve injury including paralysis can outweigh the benefits (Botwin et al., 2003).

1.5.2 Surgical management

Patients with symptoms of cervical radiculopathy should have a period of conservative management which is usually at least 6 weeks before undergoing surgical intervention. Patients can have disc protrusion of the nucleus pulposus through a defect in the annulus fibrosis on imaging (Ernst et al., 2005). Many patients have spontaneous disc resorption and most patients with or without surgical intervention eventually recover to their pre-morbid state and there is no evidence that delaying surgery worsens clinical outcomes (Persson et al., 1997). Surgical intervention comes with added risks of future spinal procedures. Patients having surgical management should have radiating sensory or motor symptoms for a period of more than 6 weeks. It is not recommended for acute radiculopathy patients with symptoms under four weeks (Savolainen et al., 1998). The main surgical treatment options for brachialgia are Anterior Cervical Discectomy (ACD), Anterior Cervical Discectomy with plating or Fusion (ACDF), Posterior Cervical Foraminotomy (PCF), Anterior Cervical Disc replacement and Anterior Cervical Foraminotomy (Chou et al., 2008). ACD with or without plating has been shown to achieve high fusion rates. Patients treated with posterior decompression techniques tend to have shorter operative times with comparable clinical outcomes (Murphy and Gado, 1972).

Each year about 2,500 operations are performed for cervical brachialgia in the UK (about 132,000 per year in the USA) (Saifi et al., 2018). Of the surgical options available ACD and PCF are performed most frequently. Owing to its anterior cervical approach, ACD comes with significant, potentially irreversible, risks of dysphagia and hoarse voice (Fountas et al., 2007). PCF avoids the risks associated with an anterior approach but has been shown to be associated with a higher incidence of post-operative neck pain (Wang et al., 2016). Presently, there is no clinical guidance based on high quality research to support which patients should undergo a surgical procedure. Specifically, it is unknown whether one operation works better than the other for certain types, lengths or locations of nerve root compression (Yousem et al., 1991). Currently the decision on which surgical procedure to undertake is based on a surgeon’s experience and preference.

1.6 Prognosis of cervical radiculopathy

Between 75% and 90% of patients with cervical radiculopathy resolve over several months with non-surgical management (Caridi et al., 2011), which makes follow up of patients with symptoms of cervical radiculopathy important. Those that do not resolve will frequently require further review and surgical intervention. This condition therefore represents a significant and growing burden on the National Health Service (Carette, 2005).

The Neck Disability Index (NDI) is a validated and widely adopted tool for assessing self-perceived functional limitation in patients with neck pain or brachialgia. It consists of ten items, each scored from 0 to 5, giving a total out of 50 that is commonly expressed as a percentage (Cleland et al., 2006; Young et al., 2009). The NDI has been used extensively in both clinical and research contexts and is recognised as a reliable outcome measure in trials of cervical spine disorders (Rodine and Vernon, 2012). A change of around 5 points (10%) is generally accepted as the minimal clinically important difference, representing a threshold for meaningful improvement or deterioration (Stratford, 1999; Young et al., 2010).

1.7 Image evaluation for cervical radiculopathy

There are various ways that patients with cervical degenerative disease can be imaged and the most common of these include plain radiographic imaging, CT, CT myelography and MRI. Plain radiographic imaging has limited use in the diagnosis of cervical radiculopathy. Occasionally, lateral flexion and extension views are used to assess cervical instability and oblique x-rays have been performed as early as 1967 to demonstrate osteophytes (Roberts et al., 2003). CT is helpful in cases where more information regarding the bony anatomy is required but it is unable to image the spinal cord or nerve roots and therefore has little role in the management of cervical radiculopathy. The standard imaging used for cervical radiculopathy is MRI or occasionally cervical CT myelography where MRI is contraindicated. The choice of imaging modality is influenced by the relative strengths of each technique in spatial resolution and contrast resolution (Lee W. Goldman, 2008; Winegar et al., 2020).

1.7.1 Plain radiographic imaging

Standard plain film radiographs can demonstrate the bony anatomy of the patient. Standard imaging is usually obtained in anteroposterior (AP) and lateral views. Oblique angles can be used to examine the neuroforamina. Occasionally flexion and extension radiographs are used to demonstrate instability and may be undertaken to determine anterolisthesis or retrolisthesis. This is classed as four millimetres of motion, in either direction, of one vertebra in relation to another or 12 degrees of angular motion. For patients where there is a possibility of fracture or infection then plain radiographs are easily performed and although they deliver a dose of ionising radiation this is a low dose at 0.12mSv for AP and 0.02mSv for lateral cervical imaging (Simpson et al., 2008). The anatomical changes that occur in patients with cervical radiculopathy cannot be visualised until late in the disease process and there is therefore little correlation with clinical manifestations and they are of little clinical use (Sabiston et al., 1987).

1.7.2 Computed tomography

Computed Tomography or CT is where X-rays from an emitter are directed at the patient and detected by an array of detectors positioned opposite the X-ray source. In modern clinical practice these are usually multi-detector CT systems, in which multiple rows of detectors acquire data simultaneously as the X-ray tube and detector assembly rotate rapidly around the patient (Lee W. Goldman, 2008). These data are quickly rotated around the patient to obtain a cross-sectional image. These “slices” are then reconstructed using a mathematical equation to form a three-dimensional image from measurements of attenuation coefficients of the x-ray beams. CT images are based on Hounsfield units where air is -1000 and bone is +1000 with all other densities in between. CT has very fine resolution but uses ionising radiation unlike MRI. Whilst CT provides excellent bone definition it is inferior to MRI when it comes to detailing soft tissue. The use of multi-detector systems contributes to improved spatial resolution, thinner slice acquisition and faster scan times, making CT particularly effective for the assessment of cortical bone, osteophytes and other fine osseous contributors to foraminal narrowing (Lee W. Goldman, 2008). For those patients with contraindications to MRI (e.g. claustrophobia or carrying permanent non-MRI compatible metallic devices such as cardiac pacemakers) a CT myelogram can be performed. This invasive technique, which requires an injection of a contrast medium into the theca (akin to a lumbar puncture) can improve diagnostic accuracy compared to CT alone (American College of Radiology, 2012).

Contrast resolution describes how well an imaging modality can distinguish between tissues with similar physical properties. In the cervical spine this is particularly important for differentiating disc material, cerebrospinal fluid, spinal cord, nerve roots and ligamentous structures. MRI has superior contrast resolution compared with CT, and this is one of the main reasons why it is the preferred modality for evaluating cervical radiculopathy, where the key clinical question is not only whether the foramen is narrowed, but also whether the exiting nerve root, disc or surrounding soft tissues are involved (Caridi et al., 2011; Winegar et al., 2020).

1.7.3 Magnetic resonance imaging

MRI was used extensively in the chemical industry before it was applied in healthcare. It is minimally invasive but is expensive to perform with reduced availability when compared with CT. The patient undergoing an MRI lies within a large electromagnet, in emergencies these can be quenched if required. Within the human body there are many tissues containing hydrogen atoms and the majority of these are within water molecules. The static magnetic field then aligns these in parallel to the field to which a radiofrequency pulse is introduced from the scanner. This causes the spin to tilt perpendicularly to the magnetic field and this will lead to an electric current or signal being generated by faraday induction in the receiver coil. The signal characteristics seen on MRI are determined principally by T1 and T2 relaxation. T1-weighted imaging reflects longitudinal relaxation, which describes the recovery of net magnetisation along the main magnetic field after radiofrequency excitation. T2-weighted imaging reflects transverse relaxation, which describes the decay of phase coherence in the transverse plane (Salvolini and Scarabino, 2006). Sometimes contrast agents are required to enhance the images obtained and the most common is gadolinium. It is used as it has seven unpaired electrons and it works by shortening T1, leading to a brighter signal, and by shortening T2, leading to a hypointense signal. Gadolinium is excreted through the renal system therefore it should be used with caution in patients with renal failure. T1-weighted images are particularly useful for anatomical detail, whereas T2-weighted images highlight tissues with higher free water content and are especially useful for demonstrating disc degeneration, fluid-sensitive pathology and nerve root or cord-related abnormalities (Salvolini and Scarabino, 2006).

The strength of the permanent magnetic field is measured in teslas (T) which is the field intensity generating one newton (N) of force per ampere (A) of current per meter of conductor. The standard magnetic fields used in routine clinical practice are 1.5T and 3T (1.5T is about 30,000 times stronger than the Earth’s magnetic field). In research, higher field strengths may be encountered including 7T (Balchandani and Naidich, 2015). There are contraindications to MRI which are based on ferrous metals or programable devices. Patients with an implanted prothesis can have heating induced from the current created by the switching magnetic field but most are scanned without issue. Very high magnetic fields have been known to lead to nerve cell depolarisation and flickering lights seen by patients. Increasing the magnetic field can improve many properties of the images obtained. Signal is proportional to the square of the static magnetic field and noise increases linearly. This in theory means that a 3T MRI should have twice as good signal to noise ratio as a 1.5T MRI however due to susceptibility effects this only leads to a 30-60% improvement. The specific absorption rate calculated as the amount of energy (joules) deposited in tissues (kg) which is proportional to the static field squared. This means that 3T leads to four times the energy within tissues as a 1.5T magnetic field however there are other factors that also influence the energy transmitted which depend on the sequence used. Higher-strength MRI scanners, such as 3T systems, often have smaller bore sizes compared to lower-field or open MRI units, which can increase issues related to claustrophobia and patient comfort, though newer wide-bore designs are helping to address this. Additionally, there is generally an inverse relationship between magnetic field strength and scan time with higher tesla machines producing a stronger signal-to-noise ratio, allowing for either shorter scan times, higher image resolution, or a balance of both, depending on the imaging protocol used (Salvolini and Scarabino, 2006).

1.7.3.1 Advanced MRI techniques

There are various additional sequences that can be performed other than the traditional T1 and T2 weighted imaging. One such sequence is diffusion tensor imaging or DTI. This uses the principles of diffusion weighted imaging (DWI) to look at the movement of water molecules (Andre and Bammer, 2010).

The principle of DWI is applied to white matter tracts as water molecules will tend to diffuse down the axon rather than through it which is termed anisotropy. Due to the presence of structured barriers like cell membranes and myelin sheaths around the nerve. DTI assesses the magnitude of this directionality of flow within a matrix. These tracts can be colour coded with transverse fibres being coloured red, anteroposterior fibres coloured green and craniocaudal fibres coloured blue (Alexander et al., 2007).

1.7.4 Gold standard cervical spine imaging

MRI is especially good in the assessment of degenerative changes in the discs (Hunt et al., 2009) due to the loss of water and proteoglycan content which cannot be detected by CT. Its superiority in contrast resolution makes it particularly valuable for assessment of the spinal cord, nerve roots, intervertebral discs and surrounding ligamentous structures (Miyazaki et al., 2008).

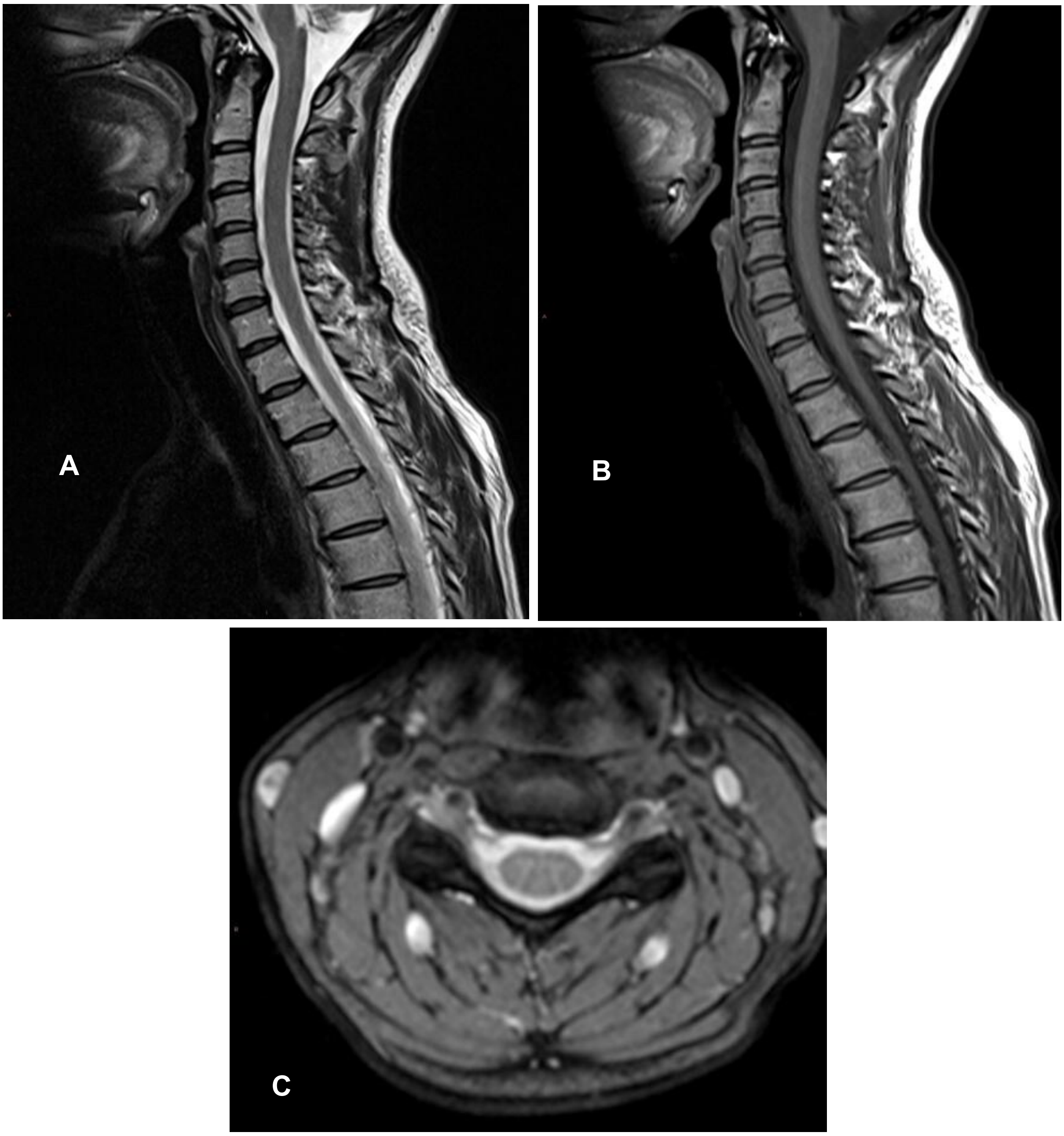


Figure 1-8 MRI demonstrating a typical clinical acquisition of a cervical spine. These views are typically orientated to the discs rather than the neuroforamina. A = T2 Sagittal B = T1 Sagittal C = T2 Axial

MRI is recommended in patients that have had cervical radiculopathy for at least 6 weeks, with symptoms in a dermatomal or myotomal distribution and have not been improving (Figure 1-8). Imaging matches surgical findings 74% of the time (Modic et al., 1986). A repeat of the MRI is not usually performed unless there has been significant change in symptoms, or it has been greater than six months since the previous imaging (Bush et al., 1997). Not only is it helpful for recognising cervical radiculopathy it can identify other neurological findings leading to symptoms. The clinician must correlate the clinical examination features with those from the MRI. In one longitudinal study, participants aged between 24 and 27 were assessed at two different points in time, separated by a seven-year interval. At the initial review, they were placed into two groups, those who reported pain in the cervical, thoracic or shoulder regions and those who were symptom-free. They were then re-evaluated seven years later to explore how their symptoms or musculoskeletal health had changed over that period. An MRI was performed at the end of the follow up period and it showed that cervical spine changes were equally common in both groups, there were 20 degenerative discs compared with 26, 14 annular tears compared with 18 and 18 disc protrusions compared with 29 in the symptomatic group compared with the asymptomatic group respectively (Siivola et al., 2002).

1.7.4.1 Limitations of MRI in the cervical spine

Standard MRI scans use sequential axial and sagittal cuts through the cervical spine separated by three millimetres. However, the path the nerve root follows through the neuroforamina is not in a standard orthogonal plane and the nerve itself is between two and three millimetres in diameter. Consequently, nerve root compression can be rather poorly demonstrated (Figure 1-9) using the standard three millimetres slice T2 axial and sagittal MRI sequences of the cervical spine (Lee et al., 2017). This reflects an important practical limitation of MRI, although it has excellent contrast resolution, standard clinical acquisitions may have insufficient spatial resolution and suboptimal slice orientation for a very small obliquely orientated structure such as the exiting cervical nerve root. It has also been reported that MRI overestimates neuroforaminal stenosis when compared to CT by between eight and 27 percent (Takasaki et al., 2009). Therefore, when performing MRI for patients they must be adequately counselled that it is highly unlikely they will have a “normal” result and that they should not become fixated on attempting to “fix” asymptomatic abnormalities that are found. If patients are not counselled, they are much more likely to disengage with conservative management and seek surgical intervention even when this is not necessary (Matsumoto et al., 1998).

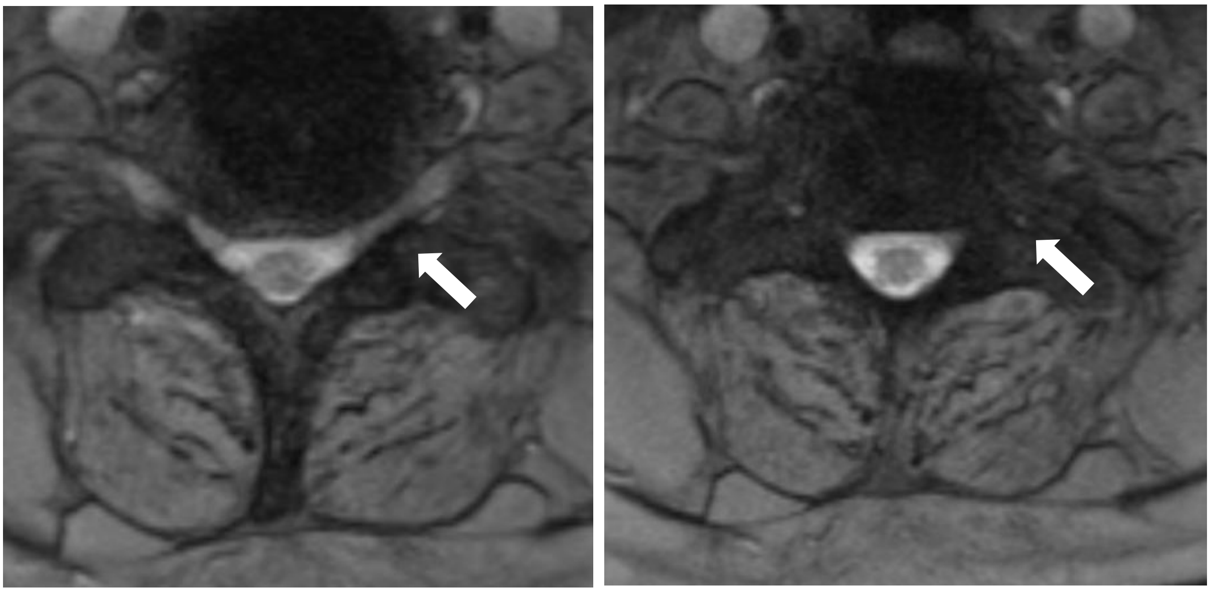


Figure 1-9 Standard T2 axial imaging showing how the 3mm slices fail to follow the orthogonal plane of the nerve root
The nerve root can be seen on the first image but not on the second image as indicated by the white arrow.

1.8 Imaging the nerve root foramen

The best way to radiologically assess the degree and location of cervical nerve root compression remains uncertain. Cervical root canal stenosis is usually reported using subjective terms such as “minor”, “moderate” and “severe”. Conventional MRI takes axial and sagittal images, and these are used to determine if there is any nerve root compression. This has been performed since 1988 and using a surface MRI coil can improve the views along the neuroforamina. The images that have been obtained have been correlated with cryosection images (frozen tissue samples) to confirm that the compression seen by MRI correlates with actual compression. The intraforaminal structures were visualised. The dorsal nerve root was demonstrated to be in contact with the superior articular process. The ventral root was found to be in contact with the uncinate process and superior articular process in the lower section of the neuroforamina below the disc level. This relationship could help explain why subtle changes in the foraminal anatomy are important rather than only disc pathology (Pech, 1988).

In cervical degenerative disease, poor visualisation of nerve roots in the neuroforamen on conventional MRI sequences is primarily due to several anatomical and technical factors. One significant issue is partial volume averaging, where thick MRI slices (e.g., 3-5 mm) lead to the averaging of small structures like nerve roots with surrounding tissues such as bones or discs, resulting in unclear differentiation of the nerve roots (Rao, 2002). Additionally, bone and ligament artifacts, particularly from the vertebrae and intervertebral discs, can cause signal drop-off, which further obscures the view of the nerve roots, especially on T1-weighted images (Winegar et al., 2020). The small size of the nerve roots also presents a challenge, as conventional MRI sequences may lack the spatial resolution necessary to distinguish them from surrounding structures like muscles or osteophytes, which are common in degenerative disease (Smith et al., 2019). Moreover, degenerative changes such as bone spurs, disc herniations, and hypertrophied facet joints can cause narrowing of the neuroforamen (as discussed above), further crowding the space and complicating nerve root visualisation (Kushchayev et al., 2018).

1.8.1 Neuroforaminal grading systems

1.8.1.1 Axial

There are several proposed grading systems, but these are rarely applied in clinical practice. Bartlett et al. (1998) reviewed 20 patients using standard axial T2-weighted MRI scans of the cervical spine, 3 grades were created; Grade 0 was the absence of foraminal stenosis, Grade 1 was osteophyte or disc contact with the nerve root and Grade 2 was >50% narrowing of the foramen. This study represents an early attempt to develop a scoring system and it was suggested that further research into Grade 2 compression was necessary to better refine how foraminal stenosis was related to nearby structures and their dimensions.

Kim et al. (2015) reviewed 96 patients using standard T2-weighted axial MRI scans of the cervical spine. 3 grades were created, Grade 0 was the absence of foraminal stenosis, Grade 1 indicated that the narrowest width of the neural foramen was >50% the width of the extra foraminal nerve root, Grade 2 indicated that the width of the neural foramen was ≤50% of the width of the extra foraminal nerve root.

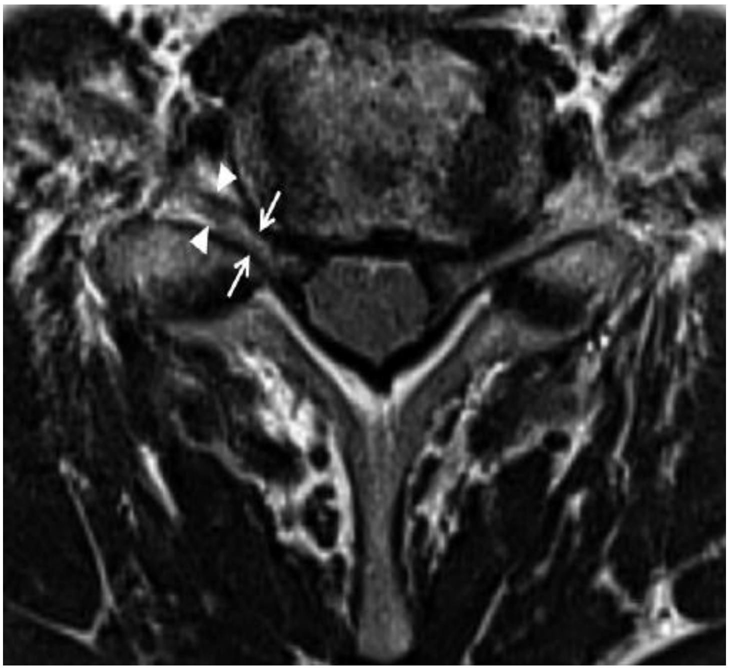


Figure 1-10 Axial T2 MRI showing compression of the cervical nerve root using the Kim grading system
Image adapted from Kim et al., (2015).

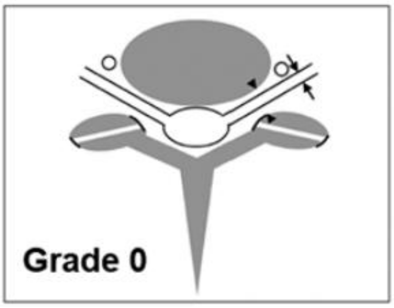
This grading criteria built upon previous methods by relating stenosis to the extra foraminal nerve root but, as with the Bartlett et al. (1998) grading, this scoring system lacks an assessment of the length or location of the compression and does not offer correlation of the radiological findings with symptoms or surgical outcome.

There have been modifications to the Kim system such as the report by Park et al. (2015). Their grades were modified as follows: Grade 0: Neural foraminal width is ≥ 80% of the extra foraminal uncompressed nerve width, Grade 1: Neural foraminal width is < 80% but > 50% of the extra foraminal uncompressed nerve width and Grade 2: Neural foraminal width is < 50% of the extra foraminal uncompressed nerve width.

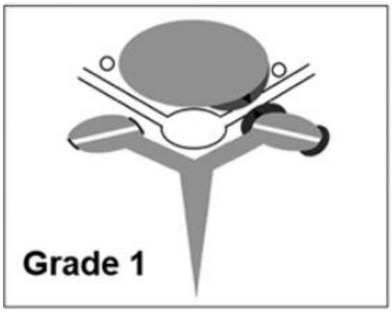
Siller et al. (2018) investigated in a group of 23 patients (11 ACDF and 12 PCF) adding in two modifications to Grade 1 and Grade 2 thus forming five grades in total to indicate whether the compression was predominantly anterior.

1.8.1.1.1 Advantages and disadvantages

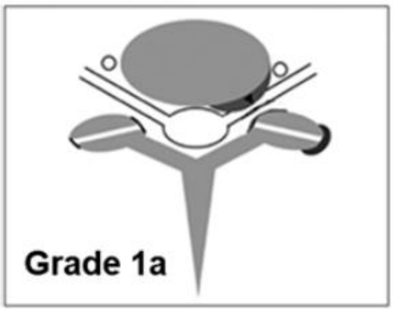
Grading neuroforaminal stenosis on axial MRI offers several advantages and disadvantages. One key advantage is its simplicity as it utilises the standard MRI sequences that are naturally acquired for patients with cervical spondylosis thus increasing applicability in most if not all spinal surgery centres. The use of axial MRI sequences, allow for clear and direct visualisation of the neuroforamen and adjacent structures, aiding in the detection of foraminal narrowing and its impact on nerve roots. However, the method also has certain limitations; one disadvantage is that it does not account for the dynamic nature of neuroforaminal stenosis, as compression can vary depending on neck position or movement, which might not be captured in a static MRI (Kim et al., 2015). Additionally, the grading may lack sensitivity in identifying mild stenosis or subtle changes, which can lead to underestimating the clinical significance of early or borderline cases (Boden, 1994). Furthermore, axial MRI may not fully capture the oblique orientation of the neuroforamen, potentially reducing the accuracy of assessment in some patients.



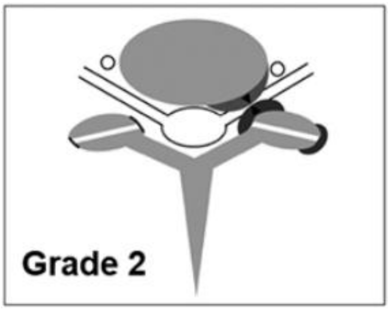
No neuroforaminal stenosis with the arrowheads depicting the narrowest width of the neuroforamina and the black arrows depicting the extraforaminal nerve root width



Non-severe neuroforaminal stenosis with the neuroforaminal width same or less than the extraforaminal nerve root width



Grade 1 with predominant anterior nerve root compression



Severe neuroforaminal stenosis with the width of the neuroforamina same or less than 50% of the extraforaminal nerve root width

Grade 2 with predominant anterior nerve root compression.

Figure 1-11 Schematic diagram of the Siller grading system

Image adapted from Siller et al. (2018)

1.8.1.2 Oblique sagittal

Park et al. (2013) reviewed 50 patients using T2-weighted oblique sagittal MRIs of the cervical spine. In this study 4 grades were created, Grade 0 was the absence of foraminal stenosis, Grade 1 was mild (<50% of root circumference), Grade 2 was moderate (>50% of root circumference) and Grade 3 was severe foraminal stenosis (nerve root collapse). This study utilised non-standard oblique MRI views that are not available in routine clinical practice, the length and location of the compression was not graded and there was no attempt to correlate findings with symptoms and surgical outcome.

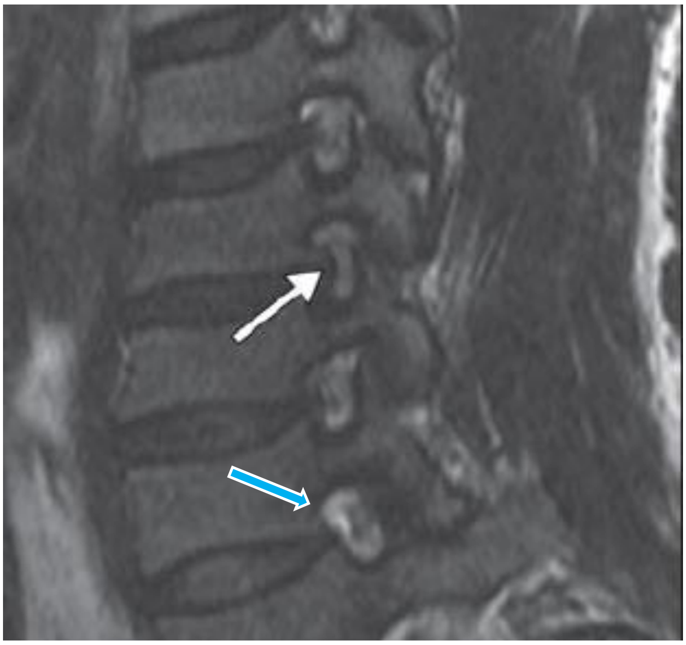


Figure 1-12 Oblique sagittal T2 MRI
White arrow indicates a disc osteophyte, narrowing the exit foramen and compressing the nerve. Blue arrow indicates an uncompressed nerve two levels below. Image adapted from Park et al. (2013)

1.8.1.2.1 Advantages and disadvantages

The oblique angle has several advantages which include visualisation of the edges of the neuroforaminal canal, the whole cross-section of the nerve and nerves at multiple levels in a single image. However, one disadvantage of the Park method is its complexity. The oblique acquisition times can be long which in most centres makes this prohibitive for general use and it increases the likelihood of movement artefacts (Yenerich and Haughton, 1986).

1.8.1.3 Diffusion tensor imaging

DTI has been shown to be a valuable tool for evaluating the brachial plexus providing microstructural information beyond conventional MRI. The brachial plexus is a complex network arising from the cervical spinal cord and can be difficult to assess with standard imaging as MRI often lacks the spatial resolution necessary to visualise subtle axonal or myelin changes (Wade et al., 2023).

Among the DTI derived parameters, fractional anisotropy (FA) is the most widely reported, reflecting the directional dependence of water diffusion and can be used as a proxy marker of white matter integrity but its interpretation can be hindered in regions with complex fibre orientation. Mean diffusivity (MD) quantifies the overall magnitude of diffusion and can pick up pathological changes such as oedema or axonal loss but can lack specificity in differentiating between causes. Quantitative anisotropy (QA) has been proposed as a more robust directional diffusion measure, which is less influenced by crossing fibres or free water contamination, making it promising for assessing exiting cervical nerve roots (Alexander et al., 2007). Restricted diffusion imaging (RDI) is able to estimate the constrained water movement within axons and may be able to act as a closer proxy for axonal density, potentially identifying early or subtle changes not apparent on other DTI metrics (Yeh et al., 2017). The isotropic value (ISO) quantifies non-directional diffusion and could help to distinguish between oedematous or CSF-related signal from true microstructural disruption (O'Donnell and Westin, 2011; Yeh et al., 2013).

Injured nerves demonstrate reduced diffusion directionality, with lower FA values indicating disorganisation of axonal and myelin structures (Marawar et al., 2016). DTI metrics are also influenced by biological and technical factors. Wade et al. (2023) showed that FA and MD vary with age and can also change along the nerve length. This can reflect physiological changes such as myelin loss and mechanical stress. Their meta-analysis revealed significant inter-study heterogeneity emphasising the need for technical standardisation and normative reference data in nerve imaging.

Moving proximally, Ellingson et al. (2014) demonstrated that patients with cervical myelopathy had reduced FA in compressed nerve roots when compared with healthy controls. This correlated with both symptom severity and radiological compression. Notably, DTI detected abnormalities even when conventional MRI appeared normal, which can suggest that this imaging modality could have greater sensitivity for early or subtle nerve damage. Similarly, Liang et al. (2019) found that FA values were lower in stenotic cervical nerve segments than in non-stenotic or healthy segments. This could reflect microstructural compromise, although no significant correlation with clinical severity was observed.

A recent systematic review and meta-analysis of 57 studies included analyses of typical DTI parameters of patients with cervical myelopathy and healthy controls. There were no measures of QA, ISO or RDI included in the pooled metrics or tables. This thesis will therefore aim to build upon the existing literature by evaluating these alongside the established tensor parameters (Mohammadi et al., 2025). So far, no research has examined how diffusion metrics in cervical neuroforaminal stenosis relate to NDI. Most have focused on clinician rated scores such as the Japanese orthopaedic association (JOA) or modified JOA (mJOA), which reflect neurological function rather than patient-reported disability. The link between DTI measures and real world functional impact therefore remains unclear (Liang et al., 2022; Mohammadi et al., 2025; B. Li et al., 2025).

Overall, in cervical radiculopathy, affected nerve roots are expected to exhibit reduced anisotropy and altered diffusivity consistent with loss of axonal and tissue integrity. Quantitative DTI may therefore provide an objective means of assessing nerve injury and if correlated with clinical outcome, could enhance both diagnostic precision and surgical planning.

1.8.1.3.1 Advantages and disadvantages

DTI offers several advantages in the assessment of cervical radiculopathy. It could provide quantitative, microstructural information on nerve root integrity that extends beyond the capabilities of conventional MRI This would enable detection of early or subtle axonal and myelin changes that may not be visible on standard imaging. Parameters such as QA, RDI and ISO may improve the robustness of diffusion assessment by reducing artefacts from crossing fibres and distinguishing true structural disruption from oedema or cerebrospinal fluid signal. These features make DTI a promising tool for the objective evaluation of nerve injury and for establishing correlations between imaging findings and clinical outcomes (Alexander et al., 2007; O'Donnell and Westin, 2011; Yeh et al., 2013).

Several disadvantages currently limit the clinical application of DTI. High spatial resolution and advanced MRI hardware are required due to the small size and complex anatomy of the cervical nerve roots. The technique is also prone to motion artefacts from swallowing, respiration and patient movement, which can significantly degrade image quality. Interpretation of DTI parameters, particularly FA, is challenging in regions with complex fibre orientation and there are no universally accepted acquisition protocols or interpretation criteria for the cervical spine (Jellison et al., 2004; Jones et al., 2013). Technical variability between scanners and imaging centres further reduces reproducibility and hampers the comparison of results across studies (Wade et al., 2023).

1.8.2 General limitations of the current scoring systems

One of the primary limitations of current grading systems for cervical foraminal stenosis is the subjective nature of interpreting imaging results. Radiologists may interpret the severity of stenosis differently based on their experience, the quality of the imaging, or individual anatomical variations. This subjectivity results in interobserver and intraobserver variability, which affects diagnostic accuracy and treatment decisions. A standardised, objective approach is lacking, leading to inconsistent patient outcomes.

While there are several proposed grading systems for cervical foraminal stenosis, no single system has achieved universal consensus. The lack of a universally accepted grading scale makes it challenging for clinicians to compare outcomes across studies, share data, and develop evidence-based treatment protocols. It is very important to accurately describe the point at which measurements are taken of the cervical neuroforamina as the shape is funnel like and therefore has significant changes dependent on the location of the cross section taken. There is no consensus regarding which method or location to use. The current published scoring systems that attempt to grade the degree of nerve compression are not well validated and therefore rarely used in clinical practice. This leads to wide variation in the data that is generated with very limited applicability between studies.

Most current grading systems are based on static imaging, which does not account for the dynamic nature of cervical foraminal stenosis. The cervical spine undergoes significant motion during daily activities, and stenosis may worsen or improve depending on the patient's posture or neck movements. Functional assessments, such as dynamic MRI or CT scans in flexion or extension, are often not incorporated into grading systems. This omission can lead to underestimation or overestimation of the severity of the condition (Muhle et al., 2001).

The reliance on imaging for grading cervical foraminal stenosis excludes other important diagnostic tools such as electrophysiological studies. Current systems do not integrate data from nerve conduction studies or electromyography which could provide a more holistic view of the condition. This imaging-centric approach may overlook cases where nerve function is significantly impaired despite less severe radiographic findings (Sarwan and De Jesus, 2025).

1.8.3 Cervical imaging correlating with symptoms and surgical outcomes

A notable limitation of existing grading systems is their poor correlation with clinical symptoms. Cervical foraminal stenosis can present with a wide range of symptoms, from asymptomatic to severe radiculopathy. However, the severity of the stenosis as seen on imaging does not always correlate well with the patient's symptoms. Patients with mild imaging findings may experience severe pain, while those with more pronounced stenosis may be asymptomatic. This disconnect limits the utility of imaging-based grading systems in guiding treatment and predicting outcomes.

Park et al. (2014) reviewed 166 patients using the Park system and showed 99% specificity but only 39% sensitivity for the presence of clinical symptoms. Park et al. (2015) reviewed 356 patients using standard T2-weighted axial MRIs of the cervical spine. They modified the grades based on the original Kim system to attempt to correlate this with clinical outcomes. The authors could not adequately correlate the radiological score with clinical symptoms. Lee et al. (2017) compared the Park, Kim and modified Kim systems in their ability to correlate with clinical symptoms. The Park and modified Kim systems had high correlation coefficients whereas the unmodified Kim system had moderate correlation only. Clinical symptoms are usually grossly assessed in clinic and there have been no studies to date that have used validated surgical outcome measures linked with these systems. In addition to this there have been no studies that have taken this one step further and linked grades and the characteristics of the compression to guide surgical decision making. Recent years have seen use of thinner MRI slice thickness, 3D and oblique orientation acquisition but despite this there remains poor connect between imaging findings and patient outcomes.

1.9 Conclusion

Cervical degenerative spondylosis is common; it may cause radiculopathy which is unresponsive to conservative management. Patients seek surgical consultation for a more definitive treatment. They undergo MRI to look for a surgical target which may alleviate symptoms. Pre-operative MRI has been interrogated to produce grading systems but these lack:

1. Accurate correlation with clinical symptoms

2. Prediction of the response to surgery using either ACD or PCF.

1.10 Aims

This thesis aims to address some of the short falls that exist in the current literature through the following aims:

1. Systematically review the current grading systems for cervical foraminal stenosis. This will evaluate the methods currently described to image and classify cervical neuroforaminal stenosis with specific emphasis on how well imaging correlates with symptoms and predicts surgical outcome.

2. Assess current and novel grading systems and quantitative measures in a cohort of patients with cervical spondylosis. This will establish the normal foraminal and root diameters as well as the consistency of inter and intra-rater grading using the Kim and mKim grading systems in pre-operative surgical patients.

3. Investigate which morphological features of cervical foraminal stenosis in patients with cervical radiculopathy correlated best with pre-operative and post-operative surgical outcome following ACD or PCF.

4. Explore how DTI metrics within the symptomatic cervical nerve relate to functional disability as measured with NDI. Identify any differences in diffusion characteristics between the symptomatic and contralateral asymptomatic nerves, as well as between the ipsilateral and contralateral hemi-cord at the same level.

2 Systematic review of radiological cervical foraminal grading systems

2.1 Abstract

2.1.1 Study design

Systematic review

2.1.2 Objective

To evaluate the existing radiological grading systems that are used to assess cervical foraminal stenosis.

2.1.3 Summary of background data

The importance of imaging the cervical spine using CT or MRI in evaluating cervical foraminal stenosis is widely accepted however there is no consensus for standardised methodology to assess the compression of the cervical nerve roots.

2.1.4 Methods

A systematic search of Ovid Medline databases, Embase 1947 to present, Cinahl, Web of Science, Cochrane Library, ISRCTN and WHO international clinical trials was performed for reports of cervical foraminal stenosis published before 01.02.2020. In collaboration with the University of Leeds a search strategy was developed.

2.1.5 Results

6952 articles were identified with 59 included. Most of the reports involved multiple imaging modalities with standard axial and sagittal imaging used most. The grading themes that came from this systematic review show that the most mature for cervical foraminal stenosis is described by Kim et al. and Park et al.

2.1.6 Conclusion

Imaging of the cervical nerve root canals is mostly performed using MRI and is reported using subjective terminology. The Park, Kim and Modified Kim systems for classifying the degree of stenosis of the nerve root canal have been described. Clinical application of these scoring systems is limited by their reliance on non-standard imaging (Park), limited validation against clinical symptoms and surgical outcome data. Oblique fine cut images derived from three dimensional MRI datasets may yield more consistency, better clinical correlation, enhanced surgical decision making and outcomes.

2.2 Manuscript

2.2.1 Introduction

The natural process of aging leads to degenerative changes within the spine including disc prolapse, osteophyte formation, facet joint hypertrophy and ligamental thickening. All these may lead to stenosis of the cervical foramina through which the cervical nerve roots pass. Nerve root compression causes radiculopathy, the symptom of radiating arm pain is known as brachialgia, and the syndrome may lead to significant disability including loss of arm function. Brachialgia may occur at any age but patients commonly present over the age of 40 (Tumialán et al., 2010; Alvin et al., 2016). 75% of cases may resolve with conservative management (Caridi et al., 2011) but those that do not frequently require surgical intervention.

Imaging of cervical spine (through computed tomography (CT) and/or magnetic resonance imaging (MRI)) forms an essential part of the patient management. It is used to confirm the diagnosis, locate the level and region of nerve root compression and to plan for surgery. However, imaging is not without its limitations. The type, length and location of the nerve root compression is highly variable and the best way of radiologically assessing the degree and location of cervical nerve root compression, remains uncertain. The path the nerve root follows is not in a standard orthogonal plane and the nerve root diameter is small (between two and three millimetres) leading it to be poorly imaged using the routine two millimetre slice T2-weighted axial and sagittal MRI sequences of the cervical spine (Lee et al., 2017). Moreover, in the clinical setting there exists no standard objective method of assessment to describe foraminal stenosis which leads to the use of subjective terms such as “minor”, “moderate” and “severe”. Providing potentially more benefit would be the exitance of a standardised approach to the assessment of foraminal stenosis and nerve root compression that when applied to the imaging provides information on the type of operation required and that is predictive of patient prognosis and outcome. It will also provide a common framework for classifying cases.

2.2.2 Objectives

The aim of this systematic review is to evaluate the methods currently described to image and classify cervical neural foraminal stenosis with specific emphasis on how well imaging correlates with symptoms and predicts surgical outcome.

2.2.3 Methods

The PRISMA guidelines for reporting items, systematic reviews and meta-analyses (Liberati et al., 2009) were followed. The search strategy was developed with University of Leeds health science librarians with specific expertise in systematic review development.

Inclusion criteria: cervical region of the spine; radiological imaging was performed; and quantification of the cervical neuroforaminal stenosis was undertaken. Reports were excluded based upon the following exclusion criteria: duplicate publication; trauma; non-human models; and written in a language other than English.

The literature search included Ovid Medline, Ovid Medline in progress & other non-indexed citations, Ovid Medline Epub Ahead of Print, Embase 1947 to present, Cinahl, Web of Science, Cochrane Library, Clinical trials, ISRCTN registry and WHO international clinical trials registry platform. The search strategy was mapped to MESH headings and included terms and variants of the terms including but not limited to: “Cervical vertebrae”, “Stenosis”, “Radiculopathy”, “Grading”, “Park”, “Kim”, Imaging techniques including “MRI” and “CT”. Non-human reports were excluded (Table 2-1). Reports which were both qualitative and quantitative were included. PROSPERO was searched to ensure that there were no other systematic reviews that were currently on-going for this research topic. The search protocol was peer reviewed independently by two experts and searched for articles published before 01.02.2020.

1	exp Cervical Vertebrae/
2	(cervical or spinal or neck or foramen or foraminal).tw.
3	1 or 2
4	Constriction, Pathologic/
5	Spinal Stenosis/
6	stenosis.tw,kw.
7	or/4-6 [stenosis]
8	3 and 7
9	((cervical or spinal or neck or foramen or foraminal or neuroforaminal) adj3 (narrow* or constrict* or compress* or stenosis)).tw.
10	Radiculopathy/
11	(cervical adj3 radiculopath*).tw.
12	or/8-11
13	(grading or grade* or classification* or measure*).tw,kw.
14	"Severity of Illness Index"/
15	(Park or Kim or mKim).tw,kw.
16	classification.fs.
17	or/13-16 [grading systems]
18	exp Magnetic Resonance Imaging/
19	((MR or NMR) adj2 tomograph*).tw.
20	((magnetic resonance or MR or NMR or diffusion weighted) adj2 imag*).tw.
21	(("T-2 weighted" or "T2 weighted") adj2 imag*).tw.
22	((MR or NMR) adj2 tomograph*).tw.
23	(MRI or CT or CAT).tw.
24	exp Tomography, X-Ray Computed/
25	(comput* adj3 tomograph*).tw.
26	or/18-25 [imaging techniques]
27	exp Animals/ not exp Humans/
28	12 and 17 and 26
29	28 not 27

Table 2-1 Example search strategy used in Ovid Medline

Once the reports were extracted from the databases, they were loaded into a reference management system and de-duplicated. Two authors (JM and MS) independently reviewed the article titles and abstracts, then read the full text articles to confirm that they met the inclusion criteria. Disagreements arising during each stage of report selection were resolved by consensus. Data items extracted from the reports are shown in Table 2-2.

i.	Number of patients
ii.	Gender of patient
iii.	The age of the patients, the age range and the mean age
iv.	Imaging technique used such as CT, MRI or other possible imaging modalities a. Magnetic field of the MRI scanner b. Contrast medium used
v.	Angle of viewing the neural foramina such as axial, coronal, sagittal or oblique imaging
vi.	Study type
vii.	Inclusion and exclusion criteria
viii.	C-spine Assessment a. Number of levels b. The levels included
ix.	Investigators reviewing the imaging a. Number involved b. Experience
x.	Assessment method a. Named system used b. Details of system used
xi.	Analysis of grading criteria a. Inter-rater agreement assessment b. Intra-rater agreement assessment
xii.	Correlation with symptoms or surgical outcome data

Table 2-2 Items extracted from articles in systematic review

2.2.4 Results

2.2.4.1 Overview

The initial search identified 6952 articles. Removal of duplicates left 3839. There were a further 3767 articles excluded following title and abstract screening which did not meet the selection criteria. From the remaining 72 full-text articles a further 13 articles were excluded as they did not meet the inclusion criteria leaving a total of 59 articles included in the systematic review (Figure 2-1). The characteristics of the included reports that assessed cervical foraminal stenosis can be seen in Table 3.

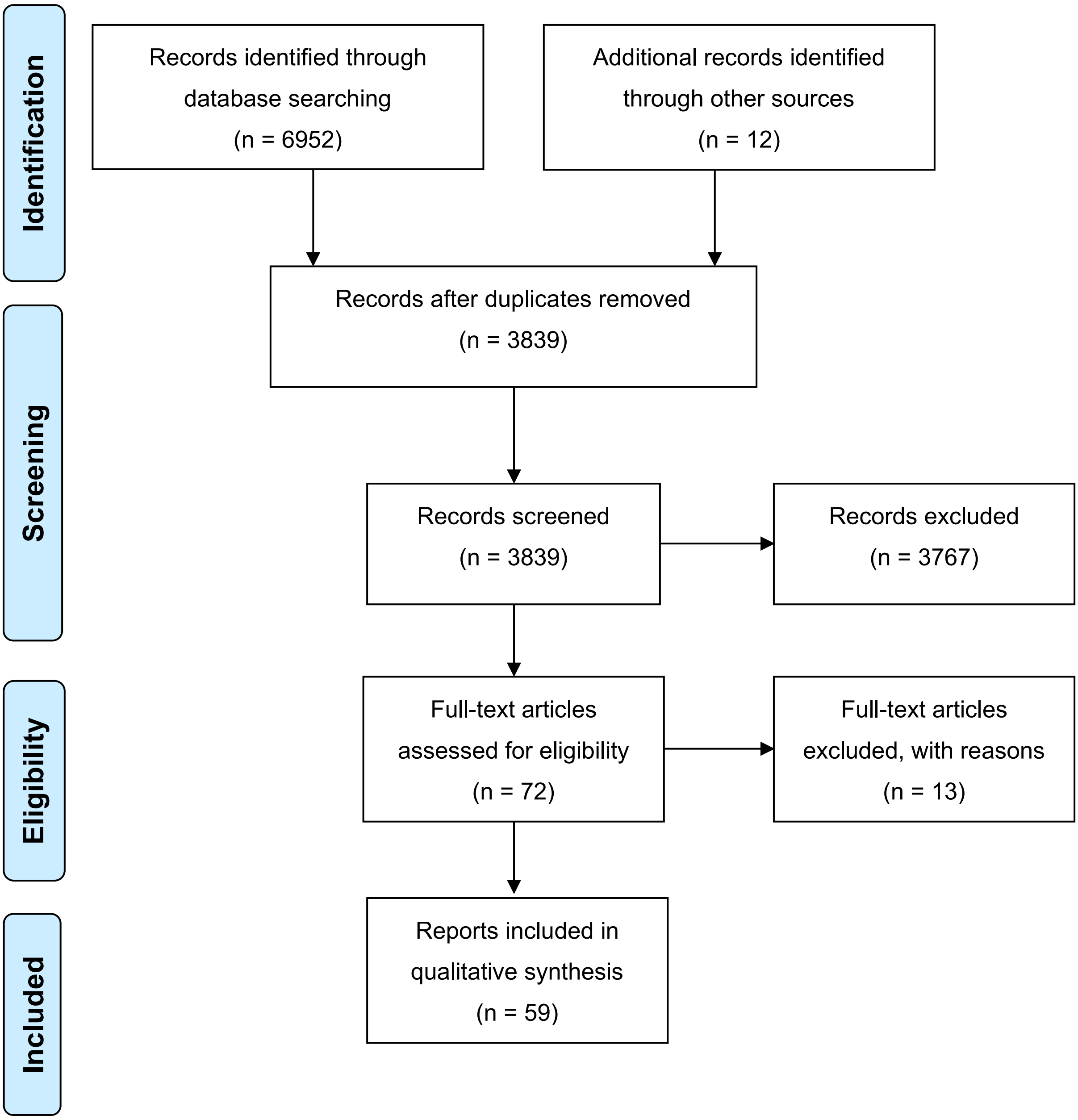


Figure 2-1 Prisma diagram depicting the flow of information through the different phases of the systematic review

Reports were from USA (40%), Europe (31%), South Korea (20%), Japan (6%), China (2%) and Canada (2%). In total 44 of the reports examined both genders, 15 reports did not give a breakdown of what proportion of their population was male or female. There were four cadaveric models with two of these not providing data on gender. There was a wide age range from 14 to 97 years.

The risk of bias for the study overall was medium as there were 59 reports in total included within this systematic review. There were 17 prospective reports, 39 retrospective reports and three where it was not clear. All the reports outlined their aims for what they wanted to achieve and only 12 were not clear with their inclusion or exclusion criteria for participants. All full journal articles included their statistical analysis and it was only the conference articles that were not explicit in how they derived their figures.

There was only one report that assessed the C1 level of the cervical spine and one that went as far caudal as the T2 level. The number of levels assessed varied by report but most commonly four levels were graded followed by six levels. Of all reports included, 20% did not indicate how many observers graded the scans but when specified, 26% were graded by two people, 14% were graded by a single person and 14% by three people, followed by 7% with six people, 5% with four people and 3% with seven people. There was a mix of observers that assessed the scans including radiologists, neurosurgeons and orthopaedic surgeons.

Most of the reports involved multiple imaging modalities; 69% used MRI, 50% used CT and 14% used plain X-rays. Most used standard axial and sagittal imaging, 53% also used non-standard oblique views along the length of the neural foramina. Those reports that used MRI favoured 1.5T over 3T and only a single report utilised 0.2T.

Report	Sample size	Report design	Age Range (Mean)	Sex		Complexity of grading system	Observer (Cons/Jnr)	C-Spine Levels (No)	Observers	Extent of testing	Imaging Technique			Angle	Grading system	Symptom Correlation
				M	F						MRI	CT	X-Ray			
Douglas-Akinwande et al (2010)	18	Retrospective	28-60 (48)	11	7	Low	C	N/A	6	Medium	1.5T	Y	N	Oblique	Other	
Grams et al (2010)	17	Retrospective	35-78 (63)	9	8	Low	C	N/A	3	Low	3T	Y	N	Standard	Other	
Schell et al (2017)	25	Retrospective	41-75 (56.6)	8	17	Low	C	C5-C7 (4)	3	Low	N	Y	N	Oblique	Other	
Dailey (1996)	4	N/A	38-54 (46.75)	3	1	High	N/A	C5-C7 (3)	1	Low	1.5T	N	N	Standard	Other	
Gu et al (2017)	36	Prospective	N (55.5)	31	5	Low	N/A	C3-T1 (5)	N/A	Low	N	Y	N	Standard	Other	
Brenke et al (2014)	79	N/A	42-64.6 (53.3)	40	39	Medium	N/A	N/A	N/A	Low	N	Y	N	Oblique	Area	Y
Roberts et al (2003)	19	Retrospective	54-81 (62.7)	12	7	Low	C	N/A (2)	7	Low	N	Y	N	Oblique	Other	
Lin et al (2013)	68	Retrospective	22-76 (48)	37	31	Low	C	C2-T1 (7)	1	Medium	1.5T	N	N	Standard	Other	
Oh et al (2014)	60	Retrospective cohort	25-59 (42.7)	35	25	Low	N/A	C3-C7 (4)	2	Medium	Y	Y	Y	Standard	Other	Y
Maulucci et al (2016)	7	N/A	48-67 (57.5)	N	N	Medium	J	C3-C6 (3)	2	Low	N	Y	N	Standard	Area	
Xu et al (2014)	54	Retrospective cohort	40-74 (52.6)	36	18	Low	N/A	C2-C6 (4)	3	Medium	1.5T	Y	N	Standard	Other	
Sneag et al (2017)	19	N/A	N (58.4)	7	12	Low	J	C2-T1 (6)	N/A	Low	3T	Y	N	Oblique	Other	
Argentieri et al (2018)	34	N/A	N (57.5)	17	17	Low	C	C2-T1 (6)	2	Low	3T	Y	N	Oblique	Other	

Report	Sample size	Report design	Age Range (Mean)	Sex		Complexity of grading system	Observer (Cons/Jnr)	C-Spine Levels (No)	Observers	Extent of testing	Imaging Technique			Angle	Grading system	Symptom Correlation
				M	F						MRI	CT	X-Ray			
Tabaraee et al (2015)	72	Retrospective	N (N)	N	N	Medium	N/A	C2-T1 (6)	N/A	Medium	N	Y	N	Oblique	Area	
Su (2017)	18	N/A	N (52.2)	7	11	Medium	N/A	C3-C7 (5)	N/A	Low	N	Y	Y	Standard	Other	
Lentell et al (2002)	20	Prospective	22-25 (23.7)	10	10	Medium	J	C2-T1 (6)	N/A	Low	1.5T	N	Y	Oblique	Area	
Park (2017)	289	Retrospective	N (50)	155	134	Medium	N/A	N/A	6	High	Y	N	N	Oblique	Park	Y
H. J. Park et al (2015)	356	Retrospective	17-80 (47)	159	197	Medium	J	C4-C7 (3)	2	High	1.5T	N	N	Standard	mKim	Y
Park et al (2014)	166	Retrospective	25-81 (46)	98	68	Medium	J	C4-C7 (3)	2	High	1.5T	N	N	Oblique	Park	Y
Park et al (2013)	50	Retrospective	19-97 (49)	37	13	Medium	N/A	C4-C7 (3)	2	Low	1.5T	N	N	Oblique	Park	
Sohn et al (2004)	7	Prospective	44-85 (65.3)	4	3	Medium	J	C1-T1 (7)	3	Medium	1.5T	Y	N	Oblique	Area	
Mao et al (2016)	10	Retrospective Case-control	N (40.3)	6	4	Medium	J	C3-C7 (4)	1	Medium	3T	N	N	Oblique	Area	
Mao et al (2016)	10	N/A	N (N)	N	N	Medium	C	N/A	N/A	Low	N	N	N	Standard	Area	
Takasaki et al (2009)	23	Retrospective	19-34 (24.52)	12	11	Medium	C	C4-T1 (4)	2	Low	0.2T	N	N	Oblique	Area	
Usa et al (2016)	11	Retrospective	19-26 (21.1)	N	N	Medium	C	C2-T1 (6)	1	Low	3T	N	N	Standard	Area	
Lee et al (2017)	289	Retrospective	20-79 (50)	155	134	Medium	C	C4-C7 (3)	6	High	1.5T	N	N	Oblique	Park	Y
Yi et al (2015)	51	N/A	17-83 (49.3)	31	20	Medium	C	C2-C7 (5)	3	Medium	1.5T	Y	N	Standard	Other	
Walraevens et al (2009)	20	Retrospective	N (N)	N	N	Medium	N/A	N/A	4	Low	N	Y	Y	Standard	Other	
Liu et al (2008)	15	Retrospective	23-49 (35)	10	5	Medium	J	C2-C7 (5)	3	Low	3T	N	N	Oblique	Area	

Report	Sample size	Report design	Age Range (Mean)	Sex		Complexity of grading system	Observer (Cons/Jnr)	C-Spine Levels (No)	Observers	Extent of testing	Imaging Technique			Angle	Grading system	Symptom Correlation
				M	F						MRI	CT	X-Ray			
Liang et al (2019)	30	Prospective	25-62 (49)	14	16	High	C	C5-T1 (4)	1	Low	3T	N	N	Standard	Other	
Lee et al (2016)	188	Prospective	14-81 (41)	80	108	Medium	J	C4-C7 (3)	2	High	1.5T	N	N	Oblique	Park Kim mKim	Y
Siemionow et al (2016)	43	Retrospective	N (57.3)	15	28	Medium	C	C3-C7 (4)	2	Medium	N	Y	N	Oblique	Area	
Jenis et al (2004)	6	Prospective	N (71.6)	N	N	Medium	C	C5-C7 (2)	N/A	Low	N	Y	N	Oblique	Area	
Kintzelé et al (2018)	74	N/A	34-79 (55)	44	30	Medium	J	C3-T1 (5)	2	Medium	3T	N	N	Standard	Park	
Weber et al (2018)	74	Retrospective	N (N)	N	N	Medium	C	N/A	N/A	Medium	3T	N	N	Oblique	Park	
Fu et al (2016)	48	Retrospective	15-91 (50.9)	23	25	Low	C	C2-T1 (6)	6	Medium	Y	N	N	Standard	Other	
Coşar et al (2008)	13	N/A	35-58 (48.6)	5	8	High	N/A	C4-C7 (3)	N/A	Low	Y	N	N	Standard	Area	
Brenke et al (2014)	34	Retrospective	N (N)	N	N	Medium	C	N/A	N/A	Low	N	Y	N	Standard	Area	
Miyazaki et al (2008)	50	Retrospective	19-69 (44)	22	28	Medium	N/A	C2-T1 (6)	4	Medium	0.6T	N	N	Standard	Other	
M. S. Park et al (2015)	26	Retrospective	50-86 (60.8)	16	10	Medium	J	C2-T1 (6)	2	Medium	1.5T	N	N	Oblique	Other	

Report	Sample size	Report design	Age Range (Mean)	Sex		Complexity of grading system	Observer (Cons/Jnr)	C-Spine Levels (No)	Observers	Extent of testing	Imaging Technique			Angle	Grading system	Symptom Correlation
				M	F						MRI	CT	X-Ray			
Janusz & Siemionow (2015)	35	Prospective	N (N)	N	N	Medium	N/A	N/A	N/A	Low	N	Y	N	Standard	Area	
Lee et al (2015)	50	Retrospective	N (N)	N	N	Medium	C	C3-C7 (4)	2	Medium	Y	N	N	Oblique	Other	
Lee et al (2015)	50	Retrospective cross sectional	N (N)	N	N	Medium	J	C3-C7 (4)	2	Medium	Y	N	N	Oblique	Other	
Kim et al (2015)	96	N/A	61-86 (68.4)	50	46	Medium	C	N/A	7	Medium	3T	N	N	Standard	Kim	
Ko et al (2018)	438	N/A	20-84 (54.3)	243	195	Medium	N/A	C4-C7 (3)	3	High	N	Y	N	Standard	Other	
Nakamura & Taguchi (2017)	104	N/A	N (55.2)	88	16	Medium	N/A	C4-T1 (4)	1	Medium	Y	Y	N	Oblique	Area	Y
Siller et al (2018)	23	Retrospective cross sectional	36-78 (59.9)	19	4	Medium	C	C2-T1 (6)	N/A	Medium	Y	N	N	Standard	mKim	Y
Kitagawa et al (2004)	7	Retrospective	25-42 (31)	7	0	Medium	C	C3-C7 (4)	1	Low	N	Y	N	Oblique	Area	
Mizouchi et al (2014)	42	Retrospective	N (N)	N	N	Medium	N/A	C4-T2 (5)	1	Medium	N	Y	N	Standard	Area	Y
Chang et al (2017)	5	Prospective	27-31 (N)	3	2	Medium	J	C3-C7 (5)	1	Low	N	Y	Y	Standard	Area	
Freund et al (2013)	25	Retrospective	N (N)	N	N	Low	J	N/A	4	Low	Y	N	Y	Oblique	Other	
Anderst (2012)	1	Retrospective	N (N)	N	N	Medium	J	C2-C7 (5)	N/A	Low	N	Y	N	Standard	Area	
Kim et al (2017)	40	N/A	22-81 (50.8)	23	17	Medium	C	C2-T1 (6)	3	Medium	3T	N	N	Oblique	Park Kim	
Ray et al (2015)	64	N/A	24-70 (48.1)	33	31	Medium	C	C3-T1 (5)	2	Medium	Y	N	N	Oblique	Area	Y

Report	Sample size	Report design	Age Range (Mean)	Sex		Complexity of grading system	Observer (Cons/Jnr)	C-Spine Levels (No)	Observers	Extent of testing	Imaging Technique			Angle	Grading system	Symptom Correlation
				M	F						MRI	CT	X-Ray			
He et al (2018)	110	Prospective	N (N)	N	N	Low	C	N/A	N/A	High	1.5T	N	N	Standard	Other	
Yeni et al (2017)	11	Retrospective	35-75 (N)	4	7	Medium	C	C3-C7 (4)	N/A	Low	1.5T	N	N	Oblique	Area	Y
Y. Yeni et al (2016)	24	Prospective	28-71 (N)	6	18	Medium	C	C3-C7 (4)	N/A	Low	N	Y	N	Standard	Area	
Y. N. Yeni et al (2016)	5	Retrospective	27-31 (N)	3	2	Medium	N/A	C3-C7 (4)	N/A	Low	N	Y	N	Standard	Area	
Smith et al (2016)	13	Prospective	21-67 (56)	9	4	Medium	J	C2-T1 (6)	2	Low	N	Y	N	Oblique	Area	

Table 2-3 Summary of study characteristics

2.2.4.2 Measurements of the cervical neural foramina

The neuroforamina were described as oval in shape having a width: height ratio of approximately 2:3. This is generally continued throughout the cervical spine with the CSA of the foramina decreasing cranio-caudal (Lentell et al., 2002). The mean cervical foraminal diameter for healthy participants on MRI was shown to be 4.36mm (±1.21mm) and on CT 5.33mm (±1.39mm). Those with stenosis (defined by expert opinion) were found to have a diameter on MRI of 2.21mm (±0.64mm) and on CT 2.86mm (±0.71mm) measured using electronic callipers. This showed a discrepancy of 18.2% for healthy individuals and 22.8% for those with stenosis (Grams et al., 2010). Oblique CT of the neuroforamina obtained from cadavers determined that the CSA was a minimum of 33mm^2 up to a maximum of 55.5mm^2.

The CSA of the neural foramina can change with neck movement. Extension of the cervical spine was reported to worsen symptoms by decreasing the area whilst flexion improved symptoms by increasing the area. This indicates that nerve compression occurs most frequently during extension of the neck and foraminal width is smaller than height. Following extension reducing this dimension further may increase the likelihood of crossing a threshold leading to radiculopathy (Chang et al., 2017). C4/5 undergoes the greatest percentage change, being the main pivot point, with a change in height of 26%, width of 35% and area of 31% between flexion and extension.

Measurements in the axial plane of MRIs demonstrate that the foraminal diameter is nearly 20% more stenosed than comparative CT imaging (Verstraete et al., 1989). Using oblique views allows appreciation of the true CSA (Tabaraee et al., 2015).

2.2.4.3 CT and MRI modalities

Cadaveric reports correlating MR and CT have investigated global degeneration of the cervical spine with disc degeneration categorised as Grade I to V. There was a statistically significant correlation between worsening degeneration of the discs with neuroforaminal width, area and osteophyte spurs and increasing category of nerve compromise with decreasing neuroforaminal width and area (Frymoyer et al., 1989; Sohn et al., 2004).

When gross estimates of neuroforaminal stenosis in 25% increments are used to compare CT with MRI the inter-rater kappa correlation was shown to be comparable (Douglas-Akinwande et al., 2010). MRI can identify radiological evidence of root compression where the nerve could be seen and was compressed by the surrounding disc or osteophytes or where there was encroachment of the lateral recess or neuroforamina (Lin et al., 2013). Herniation of the intervertebral discs was measured using four grades of normal, bulging, protruding or extruding. It was shown that there were no discernible differences between the two different imaging techniques for interpretation of disc pathology (Yi et al., 2015). When evaluating facet trophism and arthrosis it was found that facet arthrosis was better identified on CT than MRI however facet trophism was equally identified on both (Xu et al., 2014).

2.2.4.4 Assessment using non-standard imaging

Axial and coronal fast spin echo multiplanar short tau inversion recovery (FMPIR) sequences have showed increased signal intensity in the nerve for several centimetres when compared to unaffected nerves and was a possible way to identify a compressed nerve which was causing symptoms (Dailey, 1996). Coronal oblique views have been attempted rather than sagittal oblique scans but delivered poor inter-rater kappa correlation (Freund et al., 2013), as have 3D CT surface reconstruction (Schell et al., 2017). Proton density zero echo time (ZTE) 3T MRI was found to have contrast comparable to that of CT for assessment of osteophytes (Sneag et al., 2017) and it can visualise the bony anatomy of the cervical neuroforamina as easily as CT with comparable inter-rater kappa correlations (Argentieri et al., 2018). Diffusion Tensor Imaging (DTI) on 3T MRI has been used to investigate the structural changes in the cervical nerve roots however this has not been correlated with neurological outcomes (Liang et al., 2019).

2.2.4.5 Grading systems

The grading themes that came from this systematic review show that the most mature grading for cervical foraminal stenosis is in the form of systems described by Kim et al. (2015) and Park et al. (2013) which were used in 24% of the reports. Area analysis of the neural foramina was performed in 48% and global analysis of cervical degenerative disease with a focus on the neuroforamina was included in 41% of the reports.

The report by Fu et al. (2016) recruited 48 patients to develop a grading system to assess degenerative changes in the cervical spine. Each patient was assessed with an MRI scan and there were seven domains including disc hydration, disc space height, central stenosis, foraminal stenosis, end plate changes, spondylolisthesis, anterolisthesis and cord signal change. There was 75.7% inter and 81.6% intra-rater correlation. Patients were categorised into two morphological groups based on the shape of the foraminal stenosis; ‘V-Shape’ where the stenosis is narrow as the nerve enters the foramina but widens as it exits and ‘Parallel-Shape’ where the stenosis was constant throughout the cervical foramina (Gu et al., 2017).

The Kim system was first published in 2011 by a Korean team aiming to classify the compression of the nerves as they passed through the neural foramina using T2 weighted axial MR imaging. The Kim system defines three grades of compression that relate the neuroforaminal diameter to that of the uncompressed nerve as it exits the cervical neural foramina at the level of the anterior margin of the superior articular process. The grades for this system are as follows: Grade 0: Absence of neural foraminal stenosis, Grade 1: Moderate stenosis with the narrowest width of the neural foramen between 51-100% of the width of the uncompressed nerve and Grade 2: Severe stenosis with the narrowest width of the neural foramen less than 50% of the width of the uncompressed nerve. In their report Kim et al studied 96 patients using seven raters who reviewed the scans. There were two radiology trainees and five musculoskeletal radiologists with between two and 17 years of experience which led to an overall inter-rater kappa correlation of between 0.50 and 0.58.

Subsequently other teams have attempted to improve upon the Kim system by modifying it to include additional features. Siller et al. (2018) investigated in a group of 23 patients (11 ACDF and 12 PCF) adding in two modifications to Grade 1 and Grade 2 thus forming five grades in total to indicate whether the compression was predominantly anterior. There was no mention of the number of raters and no correlations were reported. They clinically evaluated patients before and after surgery. There were 49 neuroforaminal stenoses (C4/5 being the most affected at 32.7%) of which 39 were graded as Grade 2a, nine as Grade 1a, one as Grade 2 therefore indicating a majority with anterior nerve root compression. A median improvement of one MRC grade from three to four out of five was found and there was also an improvement in Odom's criteria from admission (69.6%) to final clinic (91.3%). This information was not segregated by Grade of compression.

The report by Park et al. (2015) looked to modify the Kim system and published what they called the modified Kim System. This team from Korea used T2 weighted MR imaging on a cohort of 159 patients. They considered that a nerve to foramina ratio of one did not correlate with clinical symptoms. Their grades were modified as follows: Grade 0: Neural foraminal width is ≥ 80% of the extra foraminal uncompressed nerve width, Grade 1: Neural foraminal width is < 80% but > 50% of the extra foraminal uncompressed nerve width and Grade 2: Neural foraminal width is < 50% of the extra foraminal uncompressed nerve width. They had two musculoskeletal radiologists review the scans with 11 and 13 years of experience. This report found that the inter-rater kappa correlation was overall 0.851 for the standard Kim system and 0.948 for the modified Kim system. The overall correlation with clinical symptoms was shown to be r=0.484-0.562 (moderate) for the Kim system and r=0.517-0.782 (moderate to high) for the modified Kim system (H.J. Park et al., 2015).

The path that the nerve root follows is not in a horizontal plane in the cervical region (Czervionke and Berquist, 1997). Oblique imaging has been used in plain radiographs since 1967 and in CT scans since 1982 (McAfee et al., 1982; Whitley and Clark, 2016). Park et al. (2013), developed a scoring system based on oblique MR imaging. Building on the work published by Wildermuth et al. (1998) using MR imaging and Roberts et al. (2003) using CT imaging in the lumbar spine Park used existing MRI scans reformatted to show oblique views of the neural foramina. This oblique sagittal grading system based on T2 weighted imaging involves the quantification of the obliteration of perineural fat. The four grades for this system were; Grade 0: No neural foraminal stenosis, Grade 1: Mild foraminal stenosis and no morphological changes. Less than 50% perineural fat obliteration around the nerve root circumference, Grade 2: Moderate foraminal stenosis and no morphological changes. Greater than 50% perineural fat obliteration around the nerve root circumference and Grade 3: Severe foraminal stenosis showing morphological changes or nerve root collapse. The Park system showed overall correlation with clinical symptoms in a cohort of 166 patients of between r=0.630 and r=0.653 (Park et al., 2014) and when repeated in a larger cohort of 289 patients clinical manifestations were found to be between r= 0.570 and r=0.715 (Lee et al., 2017; Park, 2017).

Park et al. (2015) used a similar grading system based on the one above but with greater simplicity to include normal, foraminal stenosis or indeterminate if the rater was not sure. The report defined foraminal stenosis as simply obliteration of the perineural fat but unlike Park et al. (2013) they did not quantify the extent of obliteration. They had inter-rater kappa correlations of 0.557 for axial alone, 0.412 for sagittal alone, 0.606 for axial and sagittal views (the highest for this report) and 0.556 for oblique sagittal views when two spinal surgeons graded the scans.

A conference article by Lee et al. (2015) reviewed 50 patients and although not referenced, appeared to try and adapt and combine the Kim and Park systems using assessment of morphology on the axial images alone and extent of nerve root compression from both axial and oblique sagittal imaging. The grades were as follows: Morphology on T2 axial scans (A: No stenosis, B: Focal type with compression <50% of foraminal length and C: Diffuse type with compression >50% of foraminal length), extent of compression on T2 axial scans (Grade 0: No compression, Grade 1: Nerve root compression is <50% of extra-foraminal diameter and Grade 2: Nerve root compression is >50% of extra-foraminal diameter) with the third criteria being extent of compression on T2 oblique sagittal scans (Grade 0: No compression, Grade 1: Max compression does not pass the midline or interpedicular space and Grade 2:

Compression passes midline or severe deformation of nerve). The morphology part of the system demonstrated an inter-rater kappa correlation of 0.67-0.88 and the extent of compression was 0.55-0.80 for the axial and 0.69-0.86 on the oblique sagittal imaging. Ko et al. (2018) used the axial grading scheme from Lee et al. (2015) but applied it to CT scans rather than MRI. They had a cohort of 438 patients and three orthopaedic surgeons (one junior and two senior) graded the scans with inter-rater kappa correlation reported as 0.84 for morphology and 0.86 for the extent of compression.

The pure Park system has been assessed in eight reports and the system was used by a minimum of two raters up to a maximum of six. In the report by Lee et al. (2017) reviewing 289 patients by six raters they demonstrated the lowest inter-rater kappa correlation of 0.80 but it has been shown to be as high as 0.94 by Kintzele et al. (2018) albeit in a smaller patient cohort of 74 patients with two raters.

In the report by Lee et al. (2016), who reviewed a patient cohort of 188 to compare all three common grading systems, Park, Kim and modified Kim, there were two musculoskeletal radiologists with experience of 10 and 15 years that reviewed the images. Inter-rater kappa correlation was highest for the Park system at 0.913 (0.856–0.970) followed by the modified Kim system 0.823 (0.745–0.902) and then the standard Kim system 0.769 (0.688–0.851). It was shown that 51 patients had neurological manifestations. The correlation coefficient for the Park system was r=0.737 and r=0.741 (higher than that in Park et al. (2014)) , Kim was r=0.658 and r=0.768 and the modified Kim was r=0.714 and r=0.764.

2.2.5 Discussion

MRI is the imaging modality of choice for assessing soft tissue detail including degenerative changes and nerve roots. It is inferior to CT in its ability to outline bone and osteophytic features and it can overestimate the osseous contribution to foraminal stenosis (Schell et al., 2017). This limitation is however lessening due to new developments such as ZTE-MRI (Walraevens et al., 2009).

The cervical nerve roots exit obliquely to standard axial and sagittal imaging. Oblique imaging has been performed as early as 1967 using plain film x-rays and 1982 using CT. Oblique imaging has been shown to decrease inter-observer variability when assessing cervical foraminal stenosis. Oblique sequences can add complexity to the MRI protocol (Park, Kim, S.-Y. Lee, et al., 2013) but if a volumetric three dimensional MRI is performed the scan time is not significantly different. Each sequence takes around three minutes, whereas volumetric data can be obtained in around the same time if reformatting time is excluded. The time to reformat is falling rapidly with the increasing processing power of modern-day computing technology. This can then be used to generate the traditional axial and sagittal images as well as oblique views with very little difference in image fidelity (Lee et al., 2016). During flexion and extension the calibre of the neuroforamina changes significantly (2017). Extension of the neck can decrease the neuroforamina by more than 10% (Sohn et al., 2004). The standard recumbent position of a patient with neutral neck position used for most MRI scans may therefore underestimate the degree of foraminal stenosis however this motion is difficult to facilitate with patients restricted by a necessary neck coil.

The normal neuroforamina has been described as having the narrowest width on entry and it then widens towards the exit (Tanaka et al., 2000). The shape of stenosis may be important when making decisions relating to surgical decompression of the nerve (2017). It is difficult to fully decompress the nerve when the stenosis runs throughout the neuroforamina as in the parallel-shaped stenosis rather than predominantly focused proximally. It has also been demonstrated that this middle zone is significant in the development of radiculopathy (Sohn et al., 2004). It is unclear whether anterior or posterior surgical decompression is superior for different types of stenosis.

The current clinical method for grading foraminal stenosis is often subjective and reported by radiologists as mild, moderate or severe. It has been shown that around 10% of cases are reported as abnormal in asymptomatic patients and a similar number reported as normal in symptomatic patients (Brinjikji et al., 2015).

The Kim system showed excellent inter-rater correlation and used only axial imaging. The Park system reports higher inter-rater correlation but relies on oblique imaging which is not always available. In the report by Lee et al. (2016) it was shown that there were discrepancies between the Park, Kim and modified Kim systems where the Park system indicated that the neuroforaminal stenosis was Grade 3 but the Kim and modified Kim systems determined stenosis to be Grade 1, patients were shown to have neurological symptoms more in keeping with an increased severity of stenosis. The Kim and Park grading systems have been shown to correlate with symptoms but have not been used in prospective trials to assess surgical outcomes or in randomised trials to guide the surgical approach.

A standardised, reproducible and accurate method for imaging and reporting on foraminal stenosis could improve diagnosis and inform surgical decision making especially with regards to whether to perform surgery from the front or the back of the neck. There is a clear need to improve the imaging and reporting of cervical foraminal stenosis.

2.2.6 Conclusions

Imaging of the cervical nerve root canals is mostly performed using MRI and is reported using subjective terminology. The Park, Kim and Modified Kim systems for classifying the degree of stenosis of the nerve root canal have been described. The clinical application of these scoring systems is limited by their reliance on non-standard imaging (Park), limited validation against clinical symptoms and very limited validation against surgical outcome. Oblique fine cut images derived from three-dimensional MRI datasets may yield more consistency, better clinical correlation, enhanced surgical decision making and outcomes.

3 Consistency of radiological grading of cervical foraminal stenosis

3.1 Abstract

3.1.1 Background

The degree of cervical foraminal stenosis on MRI scans may be measured and categorised using the Kim or modified Kim methods. These grading scales have not previously been validated in a cohort of patients awaiting surgery.

3.1.2 Objectives

To establish the normal foraminal and root diameters as well as the consistency of inter and intra-rater grading using the Kim and modified Kim grading systems in pre-operative surgical patients.

3.1.3 Methods

Asymptomatic cervical nerve roots and foramina demonstrated on the pre-operative MRI scans of adult surgical patients with cervical radiculopathy were measured and categorised by six raters using the Kim and modified Kim grading methods. Repeat "second pass" measurements were made by the same assessors on the same images a minimum of one month later.

3.1.4 Results

Foraminal diameters (mm) in asymptomatic foramina were C2/C3 (mean±SD): 4.18±1.44, C3/C4 2.96±1.23, C4/C5 3.02±1.19, C5/C6 3.15±1.33, C6/C7 3.53±1.36, C7/T1 3.93±1.34. Nerve root diameters were C3 3.11±0.87, C4 2.95±0.77, C5 2.56±0.73, C6 2.26±0.76, C7 2.56±0.82, C8 3.83±0.86. Inter-rater consistency was kappa [95% CI]: Kim 0.01 [0.00, 0.03], modified Kim 0.08 [0.05, 0.10]. Intra-rater consistency was kappa [95% CI]: Kim 0.81 [0.77, 0.86], modified Kim 0.69 [0.62, 0.76].

3.1.5 Conclusions

There was poor inter-rater consistency but good intra-rater consistency when assessing the severity of foraminal stenosis on axial T2 MRI scans. Foraminal diameter was narrowest at C3/C4 and C4/C5, whereas the smallest root diameter was C5/C6. Volumetric or oblique MR may improve consistency.

3.2 Manuscript

3.2.1 Introduction

Degenerative cervical spine disease causing nerve root foraminal stenosis and nerve compression is the most common cause of cervical radiculopathy (Kim and Kim, 2010). Around 75% of patients with symptomatic cervical radiculopathy will improve over several months with conservative management (Caridi et al., 2011) but those that do not resolve will normally require magnetic resonance imaging (MRI). The degree of foraminal stenosis on MRI is used to inform the decision on whether to proceed with surgical intervention.

MRI provides high quality non-invasive imaging of the cervical spine, is the standard investigation and is widely available but effective demonstration of the site, severity and length of nerve root compression is dependent on the MRI protocol and the imaging plane selected (Lee et al., 2017). Furthermore although direct measurements can be made and several techniques have been described to categorise the severity of radiological compression including the Kim, modified Kim and Park grading systems most radiology reports still use subjective terms such as “minor”, “moderate” and “severe” (Meacock et al., 2021).

The Kim grading system uses standard T2 weighted axial MR imaging to define three grades of compression that relate the foraminal diameter to that of the uncompressed nerve as it exits the cervical neural foramen (Table 1). Kim et al. (2015) reported an overall inter-rater kappa correlation of between 0.50 and 0.58. Park et al. (2015) proposed the modified Kim system using standard T2 weighted axial MR imaging to compare the diameter of the foramen and the extraforaminal nerve root but with modified grade boundaries (Table 3-1). Park et al (2015) found that the inter-rater kappa correlation was improved from 0.85 for the standard Kim system to 0.95 for the modified Kim system. Subsequently Park has also demonstrated inter-rater kappa correlations of 0.75 to 0.99 using the Park scoring system but this requires analysis of non-standard oblique T2 sagittal MRI scans (Park et al 2015).

Grade	Kim	Modified Kim
0	Stenosis Absent	Foraminal diameter ≥ 80% of root diameter
1	Foraminal diameter 50% - 100% of root diameter	Foraminal diameter 50% - 80% of root diameter
2	Foraminal diameter ≤ 50% of root diameter	Foraminal diameter ≤ 50% of root diameter

Table 3-1 Kim and modified Kim grades for cervical nerve root compression on MRI

The aims of this study were to describe the relative sizes of the nerve roots and foramina at all asymptomatic levels in the cervical spine in a surgical cohort of patients and to evaluate the consistency of the Kim and modified Kim grading systems when used by different clinicians assessing cervical foraminal stenosis using routinely acquired pre-operative MRI.

3.2.2 Materials and methods

This study was a single institution retrospective cohort study. The study was reviewed by the research governance manager and did not require Health Research Authority (HRA) or NHS Research Ethics Committee approval. Trust organisational policies for confidentiality and data protection were followed and departmental permissions were obtained.

3.2.2.1 Study population

A surgical database was used to identify sequential patients who had undergone an anterior cervical discectomy or cervical foraminotomy for cervical radiculopathy between 1st Jan 2009 and 31st Dec 2018. The inclusion criteria were; age 18 years and over, surgical intervention including anterior cervical discectomy or posterior cervical foraminotomy, pre-operative brachialgia and an available pre-operative MRI within one year of the date of the surgery. The exclusion criteria were; cervical myelopathy, trauma, evidence of suspected or histologically proven tumour, previous cervical spine surgery, central canal stenosis, multiple level pathology, different cervical spine procedure, incomplete clinical outcome data and no available pre-operative scan.

Age, gender and MRI information was obtained from the electronic patient records.

3.2.2.2 MRI protocol

As this was a pragmatic, retrospective study the pre-operative clinical MRI scans had been performed in different hospitals and on different manufacturer's scanners. All were performed on scanners with a field strength of 1.5 Tesla. Sagittal images were acquired from the cranial cervical junction to T1, axial images were acquired from C2/C3 to C7/T1. Three (6%) scans were performed using a slice thickness of 4 mm, 47 (94%) used a slice thickness of 3 mm. In this study only the T2 weighted axial images were analysed (Table 3-2).

	Hospital 1	Hospital 2	Hospital 3	Hospital 4	Hospital 5	Hospital 6
TR/TE (ms)	3500/101	3470/85	3500/127	4000/103	3280/120	3500/120
Slice thickness (mm)	3	4	3	3	3	3
Gap (mm)	3.3	4.8	3.3	3.3	3.3	3.3
Number of Signal Averages	3	3	2	2	2	6
FOV (mm)	280 x 280	340 x 340	229 x 229	220 x 220	313 x 313	250 x 250
Matrix	384 x 307	448 x 403	384 x 269	320 x 256	276 x 200	244 x 230
Manufacturer	Siemens	Siemens	Siemens	Siemens	Philips	Philips
Field strength (Tesla)	1.5T	1.5T	1.5T	1.5T	1.5T	1.5T
Number	32	3	1	8	4	2

Table 3-2 MRI acquisition parameters from six different hospitals from which the datasets were obtained.

TR – repetition time, TE – Echo time, FOV – Field of view

3.2.2.3 Image analysis

Digital Imaging and Communications in Medicine (DICOM) axial T2 MR images were analysed using Horos (Version 3.3.5, Horosproject.org). The most diagnostic axial slice at each of six cervical levels (C2/C3 to C7/T1) was selected for analysis by an independent consultant neuroradiologist with over 10 years experience.

Six raters comprising two consultant neurosurgeons with 25 and 15 years experience, two consultant neuroradiologists with 20 and 10 years experience and two neurosurgery juniors both with five years experience. The raters were trained on how to make measurements with a detailed written description and diagrammatic representation (
Figure **3-1**). Raters independently measured distances on all the selected slices without reference to any other MRI data. Raters were blinded to the clinical history and the symptomatic surgical level of the pathology. On the "first pass" each rater provided

measurements on both sides (right and left) at all six cervical levels (C2/C3 to C7/T1). Measurements were in millimetres to two decimal places.

To determine the intra-rater correlation the same raters made a “second pass” assessment of ten of the same T2 axial images, a minimum of one month later. The second pass images were selected at random.

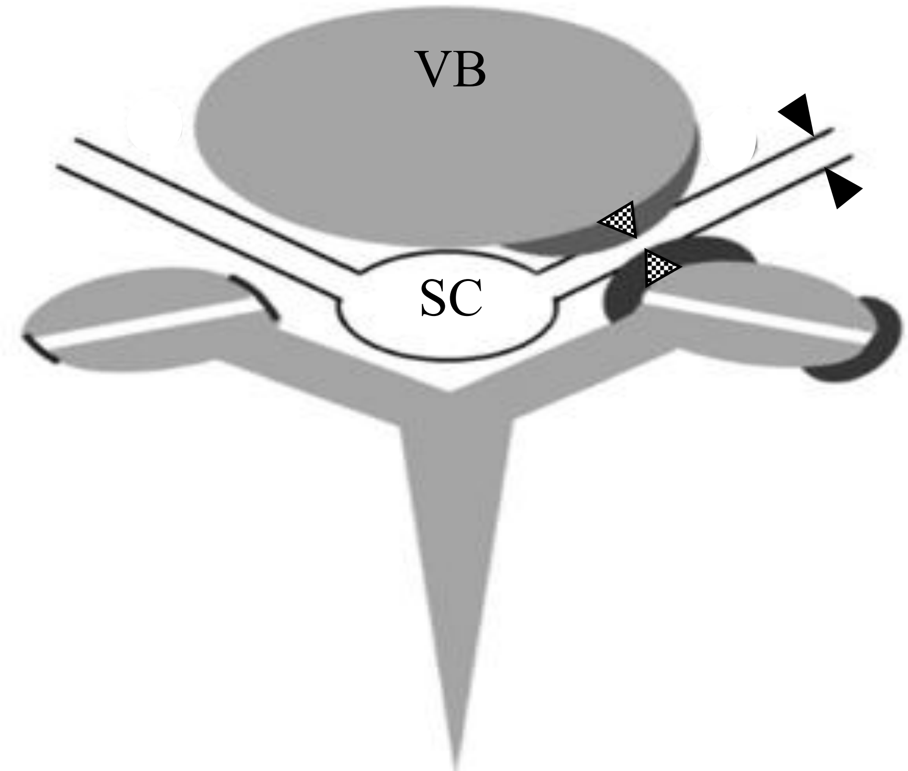


Figure 3-1 Diagrammatic representation of measurements taken on each image.

Degenerative spondylosis is indicated from a left foraminal disc/osteophyte (anterior grey crescent) and facet joint hypertrophy (posterior black crescent)

Patterned Triangle = Narrowest foraminal diameter

Solid Triangle = Maximum uncompressed nerve root diameter once it has exited the foramen

VB = Vertebral Body

SC = Spinal Cord

Adapted from Kim et al. (2015).

3.2.2.4 Statistical analysis

Mean and standard deviation values for the nerve root and foraminal diameters were calculated using the measurements obtained by the two neuroradiologists at all the asymptomatic levels.

The STATA 17 (StataCorp. 2021. Stata Statistical Software: Release 17. College Station, TX: StataCorp LLC) for windows was used for statistical analysis with independent statistical advice obtained from a professional statistician.

3.2.2.5 Inter-rater and Intra-rater agreement

Kim and modified Kim grades were calculated from the direct measurements for each level, side and rater according to the previously published methods of Kim and Park (Park, Kim, S.-Y. Lee, et al., 2013; Kim et al., 2015).

As the grading data was categorical the Kappa statistics carried out to evaluate the intra-rater and inter-rater reliability of the grading systems were as follows: Poor ($\kappa < 0.20$), Fair ($0.21 < \kappa \leq 0.40$), Moderate ($0.41 < \kappa \leq 0.60$), Good ($0.61 < \kappa \leq 0.80$), Very Good ($0.8 < \kappa \leq 1.00$) (Kundel and Polansky, 2003; Park, Kim, Y.-J. Lee, et al., 2013). Inter-rater agreement was determined by analysing the first pass grade calculated from the measurements made by each of the raters. Intra-rater agreement was assessed using second pass data from all raters combined (i.e. as a group of raters). As the raters assessed the same patients, there were multiple measurements from the same patients in these analyses, and thus the individual data values are unlikely to be independent of each other. As a result, bootstrapping methods were used to calculate confidence intervals for the kappa values. This method involves resampling from the original data multiple times and determining the results for each sample. 100 bootstrap samples were used for each analysis.

3.2.3 Results

2997 operations were reviewed, 2947 (98.3%) of the screened operations were excluded, the reasons for exclusion were; incomplete clinical outcome data (1393, 46.5%), myelopathy (706, 23.6%), multi-level disease (589, 19.7%), different procedure (101, 3.4%), not the primary surgery (79, 2.6%), no available scans (29, 1.0%) and others (50, 1.7%). 50 (1.7%) patients met the inclusion criteria (Figure 3-2). There were 26 male and 24 female patients with a mean age of 54 years (range 35-86). 13 (26%) patients had a posterior cervical foraminotomy and 37 (74%) had an anterior cervical discectomy.

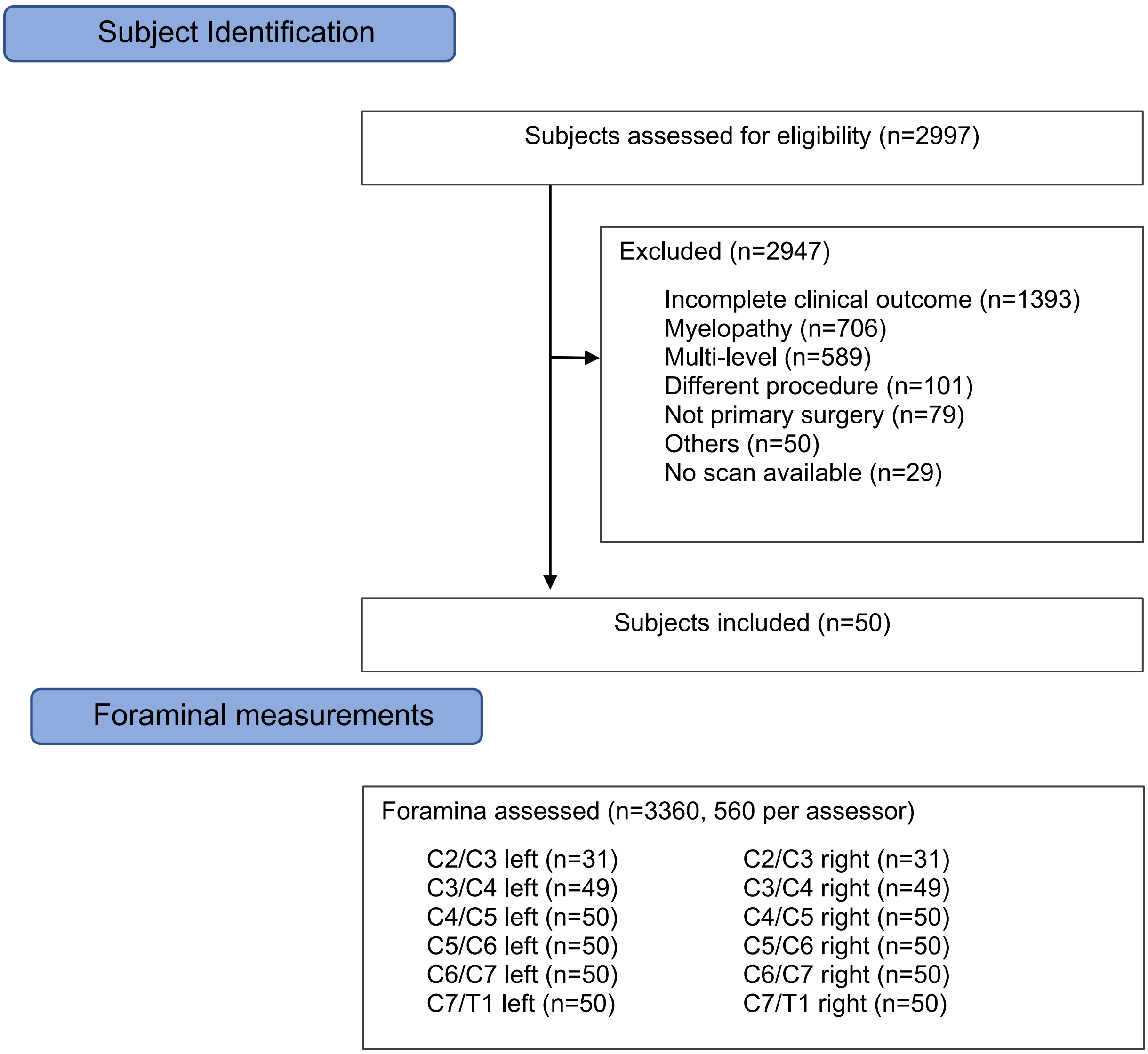


Figure 3-2 Consort diagram

All 50 patients had axial T2 imaging available for C4/C5, C5/C6, C6/C7 and C7/T1 levels, 31 patients had axial images available for the C2/C3 level and 49 patients had axial images for the C3/C4 level. The total number of foraminal grades calculated from the first pass measurements was 3360 (560 per rater). The total number of second pass grades were 720 (120 per rater).

No grade 2 stenosis was recorded using either grading system, by any rater, at any cervical level for the 50 patients. The overall distribution of Kim grades was grade 0 (1440, 43%), grade 1 (1920, 57%), grade 2 (0, 0%). The distribution of the modified Kim grades was grade 0 (1802, 54%), grade 1 (1558, 46%), grade 2 (0, 0%).

The most affected level was C5/C6 where 67/100 (67%) of foramina demonstrated at least grade 1 stenosis and the least affected was C2/C3 where 23/61 (38%) demonstrated at least grade 1 stenosis using the Kim grading system.

Using only the measurements from the neuroradiologists at the asymptomatic levels, the foraminal diameters (mm) were: C2/C3 4.18±1.44 (mean±SD), C3/C4 2.96±1.23, C4/C5 3.02±1.19, C5/C6 3.15±1.33, C6/C7 3.53±1.36, C7/T1 3.93±1.34. The nerve root diameters were: C3 3.11±0.87, C4 2.95±0.77, C5 2.56±0.73, C6 2.26±0.76, C7 2.56±0.82, C8 3.83±0.86, (Figure 3). The ratios of root diameter to foraminal diameter were: C2/C3 74%, C3/C4100%, C4/C5 85%, C5/C6 72%, C6/C7 73% and C7/T1 98%.

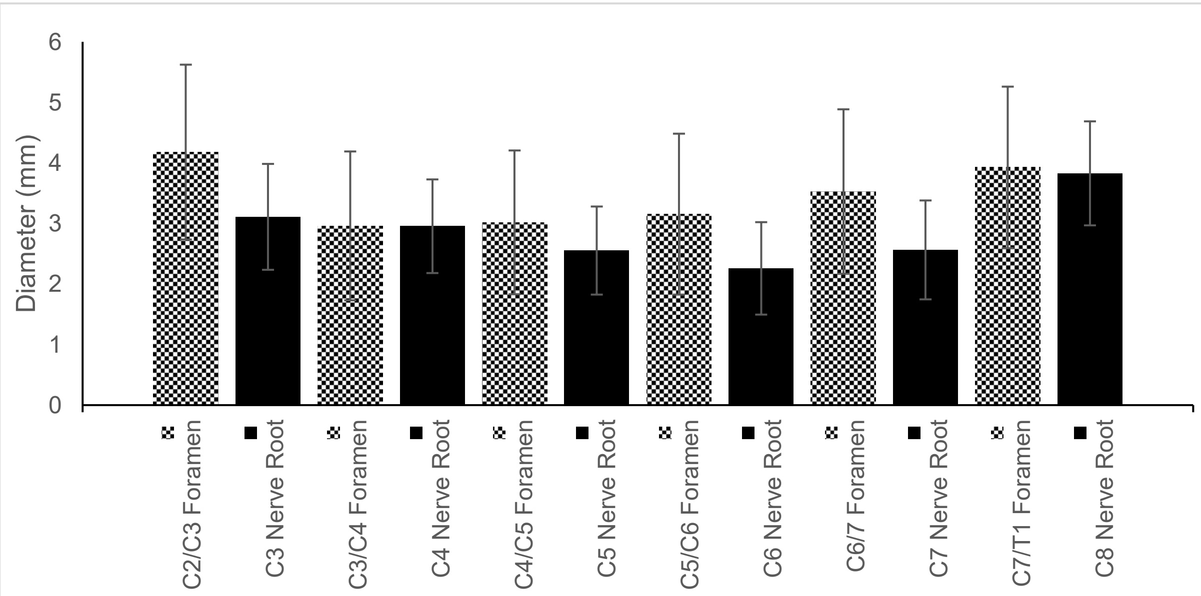


Figure 3-3 Mean (SD) nerve root and foraminal diameters at each cervical level

3.2.3.1 Rater agreement

As no rater scored grade 2 for any foramina, the results are binary - graded as either 0 or 1. Table 3-3 depicts the incidence of grade 1 provided by each rater at each cervical level. For all levels combined, rater J1 gave only one grade 1 score (0.2% of all scores given), whilst rater J2 gave almost 95% of patients grade 1. Table 3-3 also provides inter-rater correlation for the Kim and modified Kim systems and demonstrates overall poor correlation ($k<0.2$) in the allocation of grades. In contrast, intra-rater correlation was good ($0.61 < \kappa \leq 0.8$) for both the Kim and modified Kim systems.

3.2.3.2 Inter-rater agreement

Table 3 shows the inter-rater correlation for the Kim (κ 0.01 - 0.05) and modified Kim (κ 0.00 - 0.16) systems. The results demonstrate poor correlation ($\kappa < 0.2$) between raters in the allocation of grades. For all levels combined, rater J1 gave only one grade 1 Kim score (0.2% of all scores given), whilst rater J2 gave almost 95% of patients a grade 1 Kim score. The modified Kim system demonstrated overall lower grades of stenosis than the Kim system (Table 3-3).

3.2.3.3 Intra-rater agreement

A similar set of analyses were performed to quantify the intra-rater agreement. This was for both the Kim ($\kappa=0.81$) and modified Kim ($\kappa=0.69$) systems. In contrast to the inter-rater analysis this showed good ($0.61 < \kappa \leq 0.8$) correlation at every cervical level (Table 3-4).

Outcome	Rater	All levels (n=560)			C2 / C3 (n=62)			C3 / C4 (n=98)			C4 / C5 (n=100)			C5 / C6 (n=100)			C6 / C7 (n=100)			C7 / T1 (n=100)		
		G0	G1	G2	G0	G1	G2	G0	G1	G2	G0	G1	G2	G0	G1	G2	G0	G1	G2	G0	G1	G2
Kim System	J1	559	1	0	62	0	0	98	0	0	99	1	0	100	0	0	100	0	0	100	0	0
	J2	30	530	0	5	57	0	4	94	0	3	97	0	4	96	0	1	99	0	13	87	0
	R1	296	264	0	57	5	0	62	36	0	46	54	0	34	66	0	33	67	0	64	36	0
	R2	158	402	0	39	23	0	29	69	0	27	73	0	15	85	0	14	86	0	34	66	0
	N1	28	532	0	11	51	0	4	94	0	5	95	0	3	97	0	2	98	0	3	97	0
	N2	369	191	0	55	7	0	74	24	0	62	38	0	44	56	0	53	47	0	81	19	0
Kappa (95% CI)		0.01 (0.00, 0.03)			-0.04 (-0.09, 0.02)			-0.02 (-0.06, 0.01)			-0.01 (-0.04, 0.02)			0.00 (-0.04, 0.05)			-0.02 (-0.05, 0.02)			-0.05 (-0.09, -0.03)		
Modified Kim System	J1	560	0	0	62	0	0	98	0	0	100	0	0	100	0	0	100	0	0	100	0	0
	J2	103	457	0	12	50	0	16	82	0	25	75	0	15	85	0	9	91	0	26	74	0
	R1	373	187	0	60	2	0	71	27	0	68	32	0	46	54	0	47	53	0	81	19	0
	R2	289	271	0	49	13	0	55	43	0	46	54	0	38	62	0	32	68	0	69	31	0
	N1	63	497	0	15	47	0	15	83	0	14	86	0	4	96	0	4	96	0	11	89	0
	N2	414	146	0	58	4	0	81	17	0	71	29	0	55	45	0	62	38	0	87	13	0
Kappa (95% CI)		0.08 (0.05, 0.10)			-0.06 (-0.13, 0.00)			0.04 (-0.01, 0.09)			0.11 (0.07, 0.16)			0.09 (0.05, 0.13)			0.04 (0.01, 0.07)			-0.01 (-0.07, 0.04)		

Table 3-3 Inter-rater correlation for both the Kim and modified Kim systems.
This shows the results for all raters for every cervical level, number and percentage distribution and kappa values indicating strength of agreement for grade 1 responses. J = Junior Trainee, R = Radiologist, N = Neurosurgeon

Level	n	Kim System							Modified Kim System						
		First Pass			Second Pass			Kappa (95% CI)	First Pass			Second Pass			Kappa (95% CI)
		G0	G1	G2	G0	G1	G2		G0	G1	G2	G0	G1	G2	
C2 / C3	120	66	54	0	67	53	0	0.85 (0.76, 0.94)	76	44	0	77	43	0	0.69 (0.56, 0.82)
C3 / C4	120	58	62	0	58	62	0	0.77 (0.65, 0.88)	72	48	0	78	42	0	0.54 (0.36, 0.72)
C4 / C5	120	50	70	0	45	75	0	0.74 (0.63, 0.85)	66	54	0	63	57	0	0.61 (0.48, 0.75)
C5 / C6	120	40	80	0	41	79	0	0.87 (0.77, 0.97)	51	69	0	48	72	0	0.70 (0.64, 0.74)
C6 / C7	120	44	76	0	42	78	0	0.78 (0.68, 0.89)	53	67	0	60	60	0	0.75 (0.64, 0.86)
C7 / T1	120	49	71	0	50	70	0	0.85 (0.75, 0.94)	66	54	0	65	55	0	0.69 (0.64, 0.74)
All levels	720	307	413	0	303	417	0	0.81 (0.77, 0.86)	384	336	0	391	329	0	0.69 (0.62, 0.76)

Table 3-4 Intra-rater correlation for both the Kim and modified Kim systems in relation to allocation of grade 1 stenosis. This shows the results for all raters for every cervical level, number and percentage distribution and kappa values indicating strength of agreement for responses.

3.2.4 Discussion

The aims of this study were to obtain data on the diameter of the nerve roots and their respective nerve root foramina and to evaluate the reliability of the Kim and modified Kim grading systems when used by different types of clinicians assessing cervical foraminal stenosis in routinely acquired pre-operative MRI scans in surgical patients.

In this study of surgical patients with a mean age of 54, the diameter of the neural foramen at C2/C3 was the largest of the cervical foramina. The asymptomatic (i.e. non-operative) neural foramina were found to be narrowest at C3/C4 and C4/C5 and then were found to slowly enlarge towards the caudal end of the cervical spine. These results are similar to the results of Sohn et al (2004) who studied cadaveric specimens with a mean age of 65 years. However, the foraminal diameters in our study are approximately half those of an MRI study in asymptomatic participants with a mean age of 24 years (Lentell et al., 2002). This variance in foraminal dimensions may be explained by the age differences between the patient cohorts - degenerative disc disease has an increasing prevalence with age, it is present in 12 to 17% of the cervical spine discs of people in their twenties and 86 to 89% of discs in those aged over 60 (Matsumoto et al., 1998).

Diameters of nerve roots were measured beyond the foramina and this research suggests C5/C6 as the smallest cervical nerve root. This contradicts some existing literature which report an increase in nerve root diameter with cervical caudal extent (Kido et al., 2019). Additionally, the existing literature supports C5/C6 and C6/C7 as the levels most commonly affected by cervical radiculopathy (Liu et al., 2015). Whereas the present study implies that the C5/C6 and C6/C7 foramina provide the most space through which the nerve roots pass (lowest ratio of nerve root diameter to foramina diameter). This suggests that the aetiology of cervical radiculopathy may not solely depend on the mean anatomical ratio of root diameter to foraminal diameter. As suggested by Matsumoto et al. (1998), radiculopathy may also occur as result of biomechanics. C5/C6 has the greatest range of motion (Holmes et al., 1994) and at this fulcrum experiences the greatest loading forces from the head which at rest weighs about 5kg but at 60 degrees of flexion can increase to a relative weight over five times this (Hansraj, 2014).

Our results showed poor inter-rater agreement for both grading systems but good intra-rater agreement. This is in contrast to the pre-existing literature in which inter-rater kappa scores as high as 0.89 for the Kim System and 0.96 for the modified Kim System have been reported (H.J. Park et al., 2015). Poor test reliability is the most likely explanation for our results, rather than systematic or random errors. Possible causes for the different test reliability findings in this study when compared to pre-existing studies include differences in the study population and variations in technique. Beyond poor test reliability, further explanations for the discrepancy between our results and the prior literature include the fact that in our study the population group was patients awaiting surgery for symptomatic cervical radiculopathy, whereas the Kim population group consisted of 96 patients over 60 years of age without the following: a history of trauma, previous spinal operation or tumour diagnosis. Furthermore, in the present study and in contrast to prior research, no rater scored any foramina as more than grade 1 stenosis suggesting that the patients within this surgical cohort had less severe degrees of foraminal stenosis than those in previous, non-surgical studies. Additionally, in the present study we graded foramina from all cervical levels (C2/C3 to C7/T1) whereas prior studies have typically evaluated only C4/C5 to C6/C7 (Kim et al., 2015; Lee, Park, Wang, et al., 2015) due to the higher incidence of symptomatic compression at those levels (Matsumoto et al., 1998). The inclusion of all cervical levels may have reduced the proportion of severe stenosis in our population group and consequently reduced the statistical power of our study. Moreover, difficulty in defining the boundaries of the cervical foramina and nerve roots on axial MRI scans may have resulted in poor precision.

As a cervical nerve root exits the spinal canal it moves in a caudal direction at 10–15° to the axial plane (S. C. Humphreys et al., 1998), therefore as the nerve root moves laterally an orthogonal axial slice will progressively cut through higher sections of the nerve and the root diameter will appear to diminish. Furthermore, the nerve root ganglion may sometimes be visualised as a swelling of the nerve root resulting in over estimation of the nerve root diameter.

No standard imaging technique has been established for the examination of the cervical spine and protocols vary between institutions (Wolansky et al., 2005) but orthogonal axial and sagittal T2 images are typically used (Barnaure et al., 2022). We expect that the reliability of the Kim and modified Kim methods could be improved with images acquired in non-standard planes. The anatomical shape of the neural foramen is complex, it is not simply a circular window through which the nerve passes. The shape is ovoid, with the width of the foramina one half the height. The path that the nerve must traverse as it exits from the cervical region has a large medial portion which becomes narrowed in an intermediate area until once again opening up laterally (Demondion et al., 2012). These features of the foramen are not well visualised on a single orthogonal axial slice that is not aligned with the path of the nerve root.

Oblique MR acquisition at 45 degrees to the sagittal plane has been advocated by other authors (Park, Kim, S.-Y. Lee, et al., 2013; Kintzelé et al., 2018). We consider that this would improve visualisation of the foramina on the oblique sagittal images. Alternatively, orientation of images to the plane of the neural foramina may be achieved through the post-processing of 3-dimentional volumetric MR datasets but this increases acquisition and reporting time and is therefore expensive to implement (Barnaure et al., 2022).

The demonstration of foraminal stenosis is required for the diagnosis of cervical radiculopathy but correlation with the clinical features is also critical. MR imaging is normally performed with the patient supine and the neck in a neutral position (Barnaure et al., 2022). Cervical flexion increases foraminal dimensions and extension reduces them by up to 13% (Yoo et al., 1992) so neutral positioning may result in a failure to demonstrate the presence or severity of foraminal stenosis (Goodman et al., 2006).

This study has several limitations; it is a retrospective, single institution study, in which there were a large number of exclusions. The method used relied on a single axial MRI slice which differs from standard reporting where radiologists will examine axial and sagittal images. The most common reasons for exclusion were incomplete clinical outcome, the presence of myelopathy and multi-level disease. Patients without adequate clinical outcome data were excluded because this report is based on a dataset collected to support a study that requires clinical and surgical outcomes. Myelopathy and multilevel disease were excluded because the target population was patients awaiting surgery with radiculopathy from single level disease. As in previous studies, this study has reported only on radiological outcomes without correlation to clinical symptoms or surgical outcome. The ability of the Kim or modified Kim grading scales to predict symptoms or surgical outcome should be tested in future studies.

3.2.5 Conclusion

The ratio of root diameter to foraminal diameter at the asymptomatic (i.e. non-operative foramina) levels of the cervical spine in surgical patients was lowest (most space) at C5/6 and C6/7. Both the Kim and modified Kim grading systems for the assessment of cervical foraminal stenosis showed only poor inter-rater but good intra-rater agreement. Future studies should examine the reliability of these grading scales for assessing cervical foraminal stenosis using MR imaging acquired along the plane of the nerve roots rather than using orthogonal views. The ability of these scales to predict symptoms or surgical outcomes should also be evaluated.

4 Radiological cervical foraminal stenosis severity and morphology as a predictor of pre-operative function and functional surgical outcome

4.1 Abstract

4.1.1 Background

Cervical foraminal stenosis on MRI may be assessed using the Kim, modified Kim or Siller methods. This study aimed to investigate which morphological features of cervical foraminal stenosis in patients with cervical radiculopathy correlated best with pre-operative and post-operative surgical outcome following Anterior Cervical Discectomy (ACD) or a Posterior Cervical Foraminotomy (PCF).

4.1.2 Methods

Pre-operative MRIs of adults with cervical radiculopathy were assessed by six raters. The following measurements were made; uncompressed nerve root diameter, maximal compressed nerve root diameter, anterior & posterior compression, length of the neuroforaminal canal where the diameter was less than the uncompressed nerve root diameter and the distance of maximum compression from the apex of the ligamentum flavum. The Kim, modified Kim and Siller grades were calculated. Neck Disability Index (NDI) was measured pre-operatively and six weeks post-operatively. The radiological measurements and grades were compared to the pre-operative and change in NDI.

4.1.3 Results

Mean NDI was higher in female (58.2) than male patients (45.6) p=0.05. No other baseline, operative or radiological factors where significantly associated with the pre-operative NDI. The mean [±SD] post-operative NDI was 14.3 [±22.5]. This represents a change of 37.8 ($p<0.001$). The pre-operative NDI correlated strongly with the post-operative NDI but no other patient, operation or radiological factors correlated significantly. Neither pre-operative NDI or change in NDI was statistically different in those treated with ACD and those treated with PCF.

4.1.4 Conclusions

There was no association between pre-operative NDI and any of the radiological measurements or radiological grades. Furthermore, whilst surgery significantly improved NDI, for those patients with anterior compression, there was no difference in outcome between those treated with an ACD and those treated with a PCF. Current axial MRIs do not adequately assess the cervical nerve root foramina or predict surgical approach, 3D isotropic acquisition and DTI should be explored.

4.2 Manuscript

4.2.1 Introduction

Cervical foraminal stenosis is a common consequence of aging and may cause cervical nerve root compression (Rao, 2002). It may occur at any age but most patients present over the age of 40 years (Tumialán et al., 2010; Alvin et al., 2016). In the 110,000 cases of brachialgia that occur in the UK each year, around 75% resolve over several months with conservative management (Caridi et al., 2011) but those that do not resolve will frequently require imaging and surgical intervention. This condition therefore represents a significant burden on the National Health Service (Carette, 2005).

The principle surgical options for brachialgia are Anterior Cervical Discectomy (ACD) and Posterior Cervical Foraminotomy (PCF). The surgical decision on which procedure to use is frequently guided by several variables including surgeon or patient preference, complication profile, patient factors, and the findings of pre-operative magnetic resonance imaging (MRI) of the cervical spine (Malcolm, 2002). However, the morphology of foraminal stenosis varies from patient to patient (Lee et al., 2017) and it is unknown whether one operation works better than the other for certain types, lengths or locations of nerve root compression (Yousem et al., 1991). MRI provides excellent non-invasive imaging of the spine and has become the standard investigation for assessing cervical foraminal stenosis. Cervical root canal stenosis is usually reported using subjective terms such as “minor”, “moderate” and “severe” but there are several published techniques that have been used to grade the degree of cervical foraminal stenosis.

Bartlett et al. (1998) categorised cervical foraminal using T2-weighted MRI scans, however there was no attempt to measure the length of root compression or to define whether the compression was anterior or posterior and there was no correlation of the imaging findings with symptoms or outcome. Park et al. (2013) reviewed T2-weighted oblique sagittal MRI of the cervical spine. The study investigated consistency of the grading technique but not the association between stenosis grade and symptom severity or surgical outcome (Figure 4-1). Kim et al. (2015) developed a grading system based on T2-weighted axial MRI of the cervical spine and described three grades of foraminal stenosis severity, but this study again did not include clinical or surgical outcome data. Park et al. (2015) proposed the modified Kim system using standard T2 weighted axial MRI with modified grade boundaries. This study did correlate with clinical manifestations and positive neurological symptoms however, they were not quantitatively assessed. They were dichotomised into present or absent and they showed that increasing grade did not predict symptoms well.

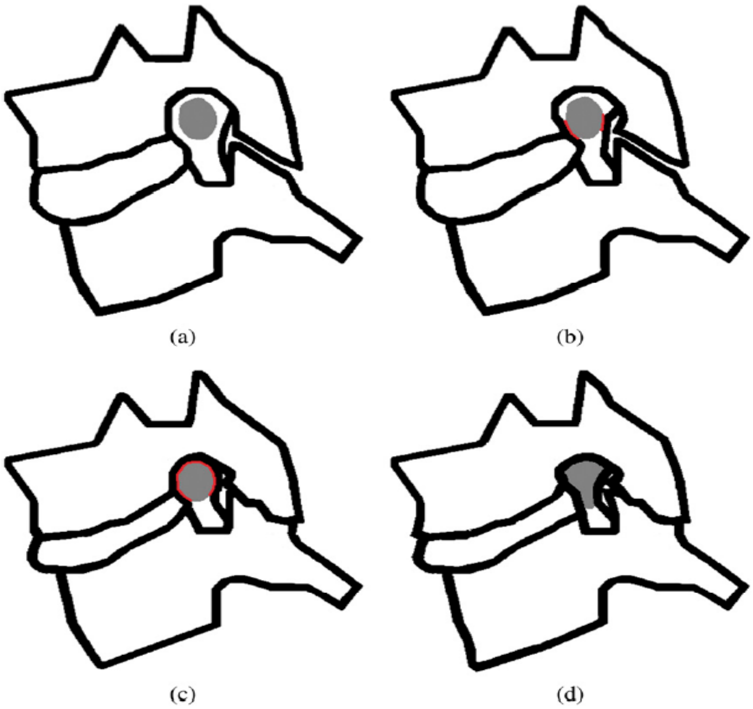


Figure 4-1 Park et al's schematic representation of their grading system for cervical neuroforaminal stenosis

(a) Grade 0, oblique sagittal plane showing no significant stenosis and no perineural fat obliteration

(b) Grade 1, mild (less than 50% of the nerve root circumference) perineural fat obliteration. No morphological change of the nerve root is seen

(c) Grade 2, moderate (above 50% of nerve root circumference) perineural fat obliteration

(d) Grade 3, collapsed nerve root, morphological change of the nerve root and severe perineural fat obliteration (Park et al, 2013).

Siller et al. (2018) investigated patients with painless motor weakness who had surgery for foraminal stenosis, dividing the unmodified Kim grading system into groups according to whether the compression was predominantly anterior or both anterior and posterior. This series is atypical in that the patients had no pain and that the C4/C5 level was the most affected site (as opposed to the literature which shows that C5/C6 is the most affected level (Fakhoury and Dowling, 2023)). Overall, for the entire study, 98% scored as showing predominantly anterior compression. Imaging grade was not significantly associated with long-term motor outcome, general performance, or quality of life. Schell et al. (2017) reviewed patients with foraminal stenosis using three-dimensional computed tomography. CT can provide exquisite bone detail and may be important for defining osteophytes as a cause of foraminal stenosis, but it lacks the fine soft tissue contrast definition that MRI affords, and which permits assessment of nerve roots, ligaments, and herniated disc material.

The Neck Disability Index (NDI) is a widely used measure and is well validated as an instrument for assessing self-rated functional disability in patients with neck pain and brachialgia. Each of ten items is scored from zero to five with a maximum overall score of 50 converted into a score out of 100 (Cleland et al., 2006; Young et al., 2009; Young et al., 2010). It has been used in over 300 publications in both clinical and research settings for quantifying this very common problem and it has been recommended as a well-suited outcome measure for clinical trials in this patient population (Rodine and Vernon, 2012). Various studies have been conducted to determine the minimally important clinical difference on NDI (Westaway et al., 1998; Riddle and Stratford, 1998; Stratford, 1999; Cleland et al., 2008; Young et al., 2009). A study by Stratford (1999) which has the highest reliability in the published literature reported a change of 5 out of 50 points (corresponding to 10%) as the minimal clinically important difference which would lead to a recommendation of surgical intervention (Stratford, 1999; Young et al., 2010). Overall, it has been shown that the literature to date has failed to investigate whether there is any correlation between the location, severity or length of nerve root compression and clinical symptoms or functional surgical outcome (Meacock et al., 2021). There is a lack of robust evidence that links pre-operative assessment of the neural foramina to surgical outcome. This study therefore aimed to investigate which morphological features of cervical foraminal stenosis in patients with cervical radiculopathy correlated best with symptoms and surgical outcome.

4.2.2 Materials and methods

This retrospective cohort study was from a single institution. The study was deemed to not require Health Research Authority (HRA) or NHS Research Ethics Committee approval by the research governance manager. Data protection policies were followed by anonymising data where possible, including gaining departmental permission and following trust organisational policies for confidentiality.

4.2.2.1 Study population

A database was created to identify surgical patients who had undergone an ACD or PCF for cervical radiculopathy between 1st Jan 2009 and 31st Dec 2018. Age, gender and MRI information was obtained from the electronic patient records.

The inclusion criteria comprised: surgical intervention (ACD or PCF), age 18 years and over, preoperative brachialgia and within one year of the surgery date a preoperative MRI.

The exclusion criteria comprised: cervical myelopathy, evidence of suspected or histologically proven tumour, different cervical spine procedure, multiple level pathology, previous cervical spine surgery, trauma, central canal stenosis, incomplete clinical outcome data and no available preoperative MRI.

4.2.2.2 Clinical outcome data

Clinical outcome in the form of NDI data was accessed through the national spine database. Patients with symptoms of radiculopathy were seen in clinic and reviewed by a neurosurgical medical professional. Only those patients with a single cervical level and symptoms that correlated with this level were chosen in this study. NDI was measured preoperatively and postoperatively at six weeks. Only those patients with preoperative and postoperative NDI scores were included within the patient cohort, all those without were excluded (Figure 4-2).

4.2.2.3 MRI protocol

Preoperative MRI scans had been performed on several different manufacturer's scanners at different hospitals. Field strength was 1.5 Tesla for all scanners. Axial images were acquired from C2/C3 to C7/T1 and sagittal from the cranio-cervical junction to T1. The maximum slice thickness was 4mm, but most scans had 3 mm T2-weighted (T2) axial slices. Only the T2 sagittal and axial images were analysed in this study (Table 4-1).

	Hospital 1	Hospital 2	Hospital 3	Hospital 4	Hospital 5	Hospital 6
TR/TE (ms)	3500/101	3470/85	3500/127	4000/103	3280/120	3500/120
Slice thickness (mm)	3	4	3	3	3	3
Gap (mm)	3.3	4.8	3.3	3.3	3.3	3.3
No of Signal Ave	3	3	2	2	2	6
FOV (mm)	280 x 280	340 x 340	229 x 229	220 x 220	313 x 313	250 x 250
Matrix	384 x 307	448 x 403	384 x 269	320 x 256	276 x 200	244 x 230
Manufacturer	Siemens	Siemens	Siemens	Siemens	Philips	Philips
Field strength (Tesla)	1.5T	1.5T	1.5T	1.5T	1.5T	1.5T
Number	32	3	1	8	4	2

Table 4-1 MRI acquisition parameters from six different hospitals from which the datasets were obtained.
TR – repetition time, TE – Echo time, FOV – Field of view

4.2.2.4 Image analysis

Horos (Version 3.3.5, Horosproject.org) was used to analyse Digital Imaging and Communications in Medicine (DICOM) axial T2 MR images. An independent consultant neuroradiologist with over 10 years experience selected the most diagnostic axial slice at each of six cervical levels (C2/C3 to C7/T1) for analysis.

In total there were six raters, these included: two consultant neurosurgeons with 25 and 15 years experience, two consultant neuroradiologists with 20 and 10 years experience and two neurosurgery juniors both with five years experience. A detailed written description and diagrammatic representation of the measurements required was used to train the raters (Figure 4-2).

Without reference to any other MRI data, raters independently measured distances on all the selected slices. Clinical history and surgical level of the pathology information was blinded to the raters. Measurements were in millimetres to two decimal places. Each rater provided measurements at all six cervical levels (C2/C3 to C7/T1) on both sides (right and left). For further information on the grading of scans please see detailed explanations in Meacock et al. (2024).

The following measurements were taken; (1) maximum uncompressed nerve root diameter once it has exited the foramen, (2) narrowest foraminal diameter (within the neuroforamina), (3) anterior length of compression, (4) anterior compression, (5) posterior length of compression and (6) posterior compression (Figure 4-2).

Observers were also asked to categorise foraminal stenosis as follows: cause of compression (disc, osteophyte, synovium or ligament), predominant location of compression (anterior, posterior) and whether the compression was in the proximal 50% or lateral 50% of the nerve root canal. Finally, the Kim and modified Kim categories were calculated according to the methods published by Kim (Kim et al., 2015) and Park (Park, Kim, Y.-J. Lee, et al., 2013).

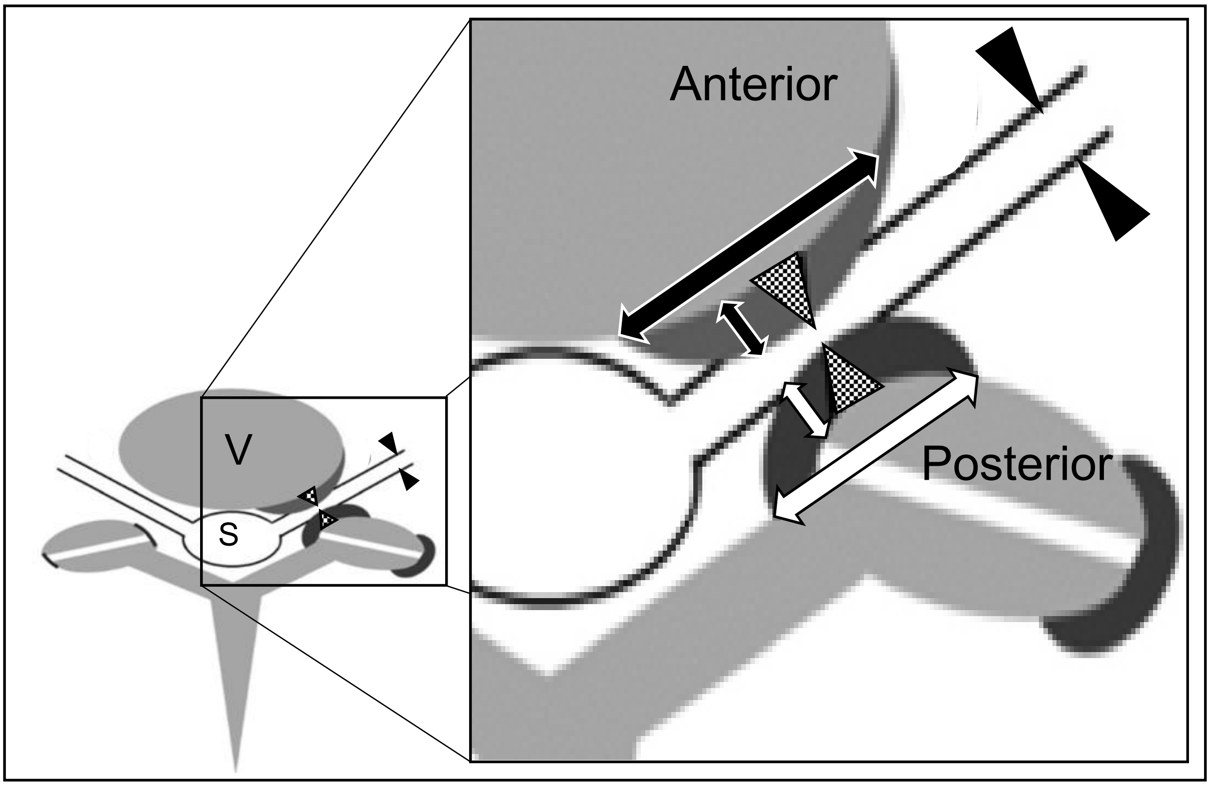


Figure 4-2 Diagrammatic representation of measurements taken on each image.

The grey and black crescents depict degenerative spondylosis with left foraminal disc bulge (grey crescent) and facet joint arthropathy (black crescent) causing left foramina stenosis, adapted from Kim et al., 2015.

Distance between the apices of the patterned triangles = Narrowest foraminal diameter

Distance between the apices of the solid black triangles = Maximum uncompressed nerve root diameter once it has exited the foramen

Long black with white outline arrow = Anterior length of compression

Short black with white outline arrow = Anterior compression

Long white with black outline arrow = Posterior length of compression

Short white with black outline arrow = Posterior compression

V = Vertebral Body, S = Spinal Cord

4.2.2.5 Statistical analysis

For statistical analysis the STATA 17 (StataCorp. 2021. Stata Statistical Software: Release 17. College Station, TX: StataCorp LLC) for windows was used with independent statistical advice obtained from a professional statistician.

Clinical correlations were tested using patient and operative factors in addition to preoperative and postoperative clinical function as determined by the Neck Disability Index score.

For the continuous imaging measurements, only the mean value from the two raters that were radiologists were used in the analyses. Whereas for the categorical variables, if the two radiologists agreed then these measurements were used in the analysis but where there was disagreement between radiologists, the most observed category from the six raters was used.

An examination of the data indicated that the NDI scores were approximately normally distributed. As a result, the unpaired t-test was used to compare the relationship between NDI scores and categorical variables with only two categories. For categorical variables with more than two categories, the analyses were performed using analysis of variance (ANOVA). The Pearson correlation method was used to examine the association between continuous variables and the NDI scores. The final analysis of baseline and outcome NDI by operation type in those with anterior compression on the MRI scan used the unpaired t-test.

4.2.3 Results

2997 operations were reviewed, 2947 (98.3%) of the screened operations were excluded due to the strict exclusion criteria. The reasons for exclusion were: incomplete clinical outcome data (1393, 46.5%), myelopathy (706, 23.6%), multi-level disease (589, 19.7%), different procedure (101, 3.4%), not the primary surgery (79, 2.6%), no available scans (29, 1.0%) and others (50, 1.7%). 50 (1.7%) patients met the inclusion criteria (Figure 3). 13 (26%) patients had a posterior cervical foraminotomy and 37 (74%) had an anterior cervical discectomy. All 50 patients had NDI recorded pre-operatively and at six weeks, there were zero patients lost to follow up.

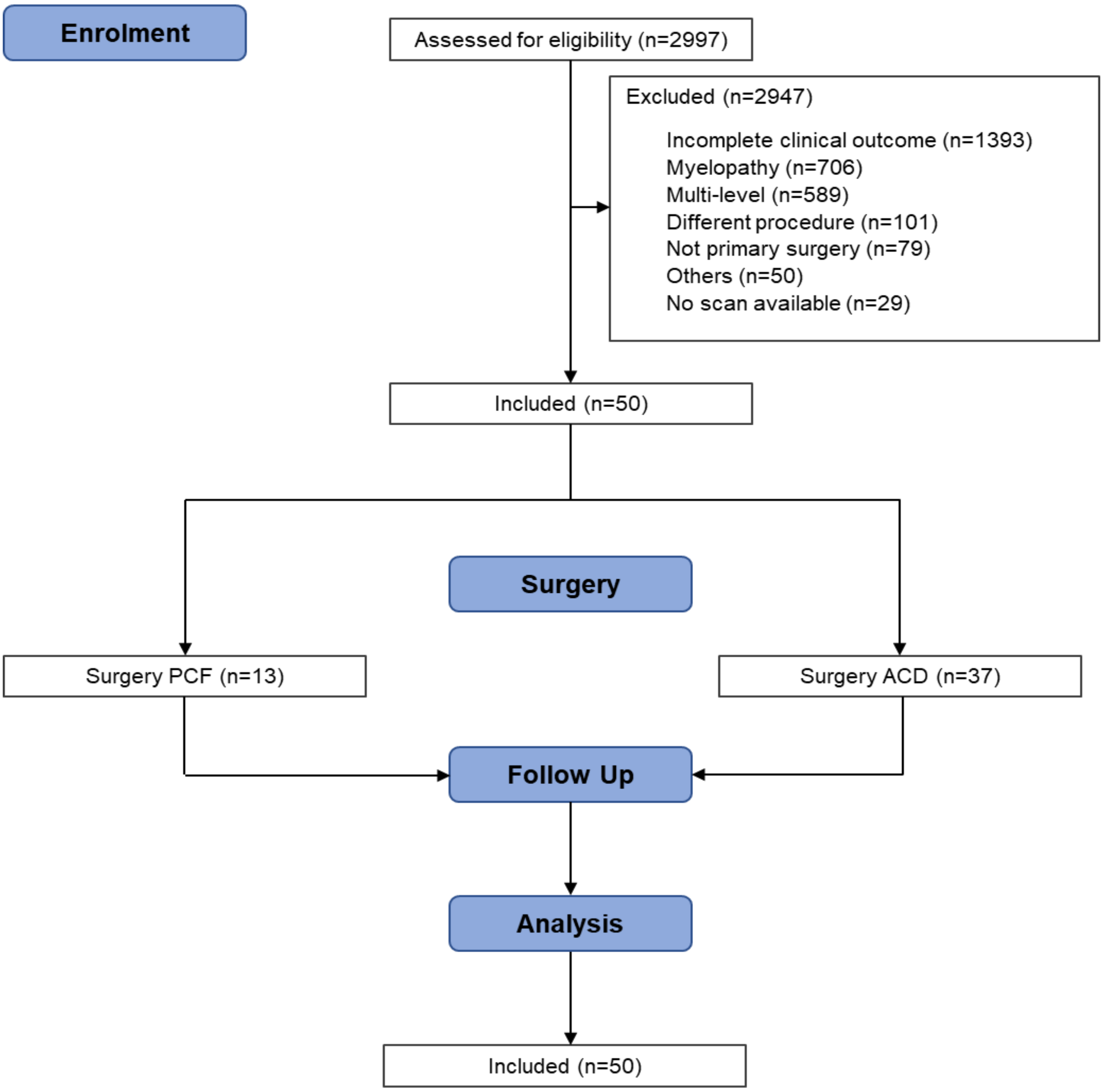


Figure 4-3 Flow diagram of patient inclusion

4.2.3.1 Baseline data

Patient baseline and operative variables are shown in Table 2. The patients had a mean [±SD] age of 49.3 years [±9.8], 26 (52%) were female and 44 (88%) were non-smokers. 27 (54%) had at least one co-morbidity, with the most frequent being obesity with nine individuals (18%), followed by type 2 diabetes (14%), hypertension (14%) and asthma (14%). The American Society of Anaesthesiology (ASA) grade (Doyle et al., 2023) was recorded as grade 1 in 29 (58%) and grade 2 in 20 (40%) patients. Only one patient had an ASA grade of 3 and none had ASA grades of 4 or 5. 40 (80%) of the operations had a consultant as primary or secondary surgeon. The most common operative levels were C5/C6 n=26 (54%) and C6/C7 n=19 (38%). 26 (52%) operations were for right sided and 24 (48%) for left sided disease.

Preoperative NDI was obtained as a measure of preoperative functional level. The mean [±SD] preoperative NDI was 52 [±22.5]. The relationship between baseline, operative and radiological variables and the preoperative NDI is shown in Table 3. Mean NDI was higher in the female (58.2) than the male patients (45.6) p=0.05. No other baseline, operative or radiological factors where significantly associated with the preoperative NDI score.

Variable		Number
Mean age [SD] in years		49.3 [9.8]
Gender	Male	24
	Female	26
Smoker	Yes	6
	No	44
American Society of Anaesthesiology (ASA) grade	1	29
	2	20
	3	1
	4	0
	5	0
Comorbidities	Obesity	9
	Diabetes	7
	Hypertension	7
	Asthma	7
	Osteoarthritis	5
	Mental health	5
	Diverticular disease	4
	Inflammatory bowel disease	3
	Gastroesophageal reflux	3
	Epilepsy	2
	Hypothyroidism	2
	Malignancy	2
	Obstructive sleep apnoea	2
	Cerebrovascular accident	2
	Hypercholesterolemia	1
	Peripheral vascular disease	1
	Rheumatoid arthritis	1
	Fibromyalgia	1
	Blood disorder	1
	Psoriasis	1
	Present	27
	Absent	23
Side	Left	24
	Right	26
Operative level	C2 / C3	0
	C3 / C4	2
	C4 / C5	3
	C5 / C6	27
	C6 / C7	16
	C7 / T1	2

Table 4-2 Patient demographics

Variable		Correlation (r)		p
Age		0.04		0.80
Variable		**n**	**NDI Mean [SD]**	**p**
Gender	Male Female	24 26	45.6 [22.8] 58.2 [20.8]	0.05
Smoker	Yes No	6 44	38.3 [27.3] 54.0 [21.4]	0.11
American Society of Anaesthesiology (ASA) grade	1 2 + 3	29 21	50.2 [20.6] 54.9 [25.1]	0.48
Side	Left Right	24 26	54.7 [21.4] 49.8 [23.6]	0.45
Operative level	C3/C4 + C4/C5 C5/C6 + C6/C7 + C7/T1	5 45	60.0 [21.4] 51.3 [22.7]	0.42
Compression cause anterior	Osteophyte Disc No cause	40 8 2	51.6 [23.7] 54.3 [20.0] 55.0 [9.9]	0.94
Compression cause posterior	Synovium Osteophyte No cause	26 2 22	51.4 [22.7] 52.5 [0.7] 53.0 [21.4]	0.97
Kim	Grade 0 Grade 1 Grade 2	6 44 N/A	61.8 [14.4] 50.8 [23.2] -	0.27
Modified Kim	Grade 0 Grade 1 Grade 2	11 39 N/A	53.4 [18.6] 51.8 [23.7] -	0.84
Siller	Grade 1a Grade 1	47 3	51.7 [23.1] 58.7 [9.5]	0.61
Variable		**Correlation (r)**		**p**
Maximum uncompressed nerve root diameter		-0.14		0.33
Narrowest foraminal diameter		-0.06		0.66
Ratio of narrowest foraminal diameter : uncompressed nerve root diameter		0.01		0.95
Anterior compression		-0.15		0.28
Posterior compression		0.03		0.84
Length of compression		-0.01		0.93

Table 4-3 Association between preoperative NDI and baseline, operative and radiological variables

Variable		**Correlation (r)**		**p**
Age		0.01		0.93
Pre-op NDI		0.52		<0.001
Variable		**n**	**Change in NDI Mean [SD]**	**p**
Gender	Male	24	35.3 [22.2]	0.46
	Female	26	40.2 [24.4]	
Smoker	Yes	6	28.7 [20.8]	0.31
	No	44	39.1 [23.5]	
American Society of Anaesthesiology (ASA) grade	1	29	35.2 [19.7]	0.36
	2 + 3	21	41.4 [27.6]	
Side	Left	24	37.5 [23.2]	0.92
	Right	26	38.2 [23.8]	
Operative level	C3/C4 + C4/C5	5	54.6 [27.9]	0.09
	C5/C6 + C6/C7 + C7/T1	45	36.0 [22.3]	
Compression cause anterior	Osteophyte	40	34.7 [24.4]	0.16
	Disc	8	49.0 [13.8]	
	No cause	2	55.0 [9.9]	
Compression cause posterior	Synovium	26	34.8 [23.9]	0.62
	Osteophyte	2	37.0 [22.6]	
	No cause	22	41.5 [23.2]	
Kim	Grade 0	6	40.3 [23.1]	0.78
	Grade 1	44	37.5 [23.5]	
	Grade 2	nil	-	
Modified Kim	Grade 0	11	34.7 [23.6]	0.62
	Grade 1	39	38.7 [23.4]	
	Grade 2	nil	-	
Siller	Grade 1a	47	36.5 [23.3]	0.11
	Grade 1	3	58.7 [9.5]	
Variable		**Correlation (r)**		**p**
Maximum uncompressed nerve root diameter		-0.17		0.24
Narrowest foraminal diameter		-0.08		0.60
Ratio of narrowest foraminal diameter : uncompressed nerve root diameter		-0.01		0.97
Anterior compression		-0.07		0.65
Posterior compression		0.06		0.70
Length of compression		0.02		0.88

Table 4-4 Association between change in NDI from baseline, operative and radiological variables

The change in NDI between the pre-operative score and the six weeks post-operative score was calculated and used as the surgical outcome measure. The mean [±SD] post-operative NDI score was 14.3 [±22.5]. This represents a change of 37.8 ($p<0.001$) and exceeds the minimal clinically important difference (a change corresponding to 10%) (Figure 4-4). The pre-operative NDI correlated strongly with the post-operative NDI but no other patient, operation or radiological factors correlated significantly (Table 4-4).

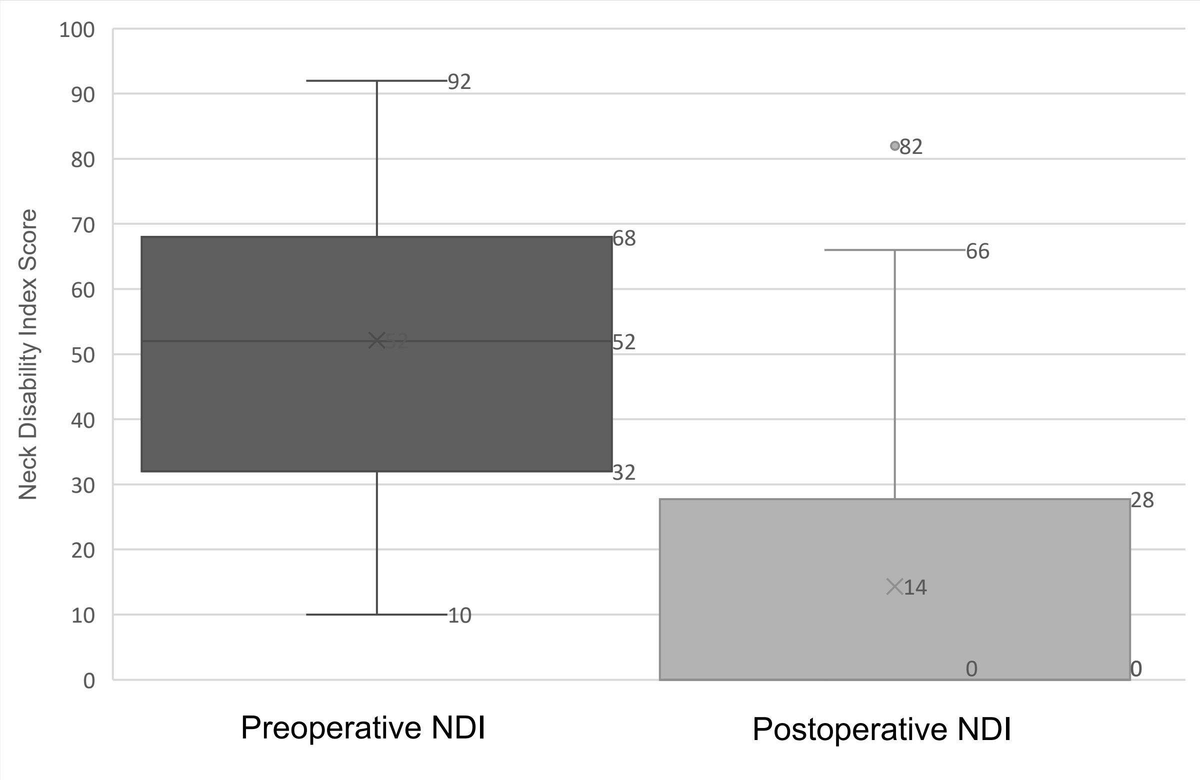


Figure 4-4 Box-plot for the Comparison of pre-operative and post-operative Neck Disability Index score

Preop Maximum NDI of 92 and Minimum 10. Median 52, First quartile 32 and Third quartile 68. Postop Maximum NDI of 82 (Greater than 1.5 IQR of 66) and Minimum 0. Median 14, First quartile 0 and Third quartile 28.

47 (94%) patients had more anterior than posterior compression classed as Siller grade 1a, 3 (6%) had more posterior compression or equal posterior and anterior compression on the preoperative MRI scans classed as Siller grade 1.

Neither preoperative NDI or change in NDI was statistically different in those treated with anterior cervical discectomy and those treated with posterior cervical foraminotomy (Table 4-5).

Variable	Operation	n	Mean [SD]	p
Preoperative NDI	Anterior Cervical Discectomy	34	52.7 [22.2]	0.65
	Posterior Cervical Foraminotomy	13	49.2 [26.0]	
Change in NDI	Anterior Cervical Discectomy	34	37.9 [23.0]	0.50
	Posterior Cervical Foraminotomy	13	32.8 [24.7]	

Table 4-5 The effect of surgical approach on subjects with predominantly anterior compression on MRI (n=47)

4.2.4 Discussion

Patients with symptoms of cervical radiculopathy are normally managed with a six-week period of conservative treatment before undergoing surgical intervention if symptoms fail to resolve. It is unknown whether anterior cervical discectomy or cervical foraminotomy works better for certain types, lengths or locations of nerve root compression (Yousem et al., 1991). Therefore, currently the decision on which surgical procedure to undertake is usually based on a surgeon's experience and preference. In this study surgery significantly improved (reduced) NDI by more than the minimal clinically important difference and the reduction in NDI was found to be significantly more in those with a higher pre-operative NDI. These findings reflect the findings of previous studies that show both Anterior Cervical Discectomy and Posterior Cervical Foraminotomy are effective operations (Matz et al., 2009; Selvanathan et al., 2015).

However, despite the overall improvement in NDI following surgery, the severity, length and position of neuroforaminal stenosis on axial MRI scans were not clearly associated with either preoperative NDI or change in NDI six weeks after surgery. Furthermore, the Kim, modified Kim and Siller methods for grading foraminal stenosis were also not found to be significantly associated with preoperative function or improvement in function six weeks post-operatively. This is an important finding as we believe it is the first time that the associations of these anatomical grading systems with preoperative function and post-operative functional improvement have been assessed.

The neural foramen is a three-dimensional passageway through which the nerve travels. Neuroforamina are reduced in size at symptomatic points when compared with asymptomatic neuroforamina. 52% of compression happens proximally, where the nerve enters the foramen, this compression most commonly arises from the uncinate process or the posterolateral region of the vertebral body. This is followed by 28% of compression from within the foramen and the remainder where the nerve exits usually occurring in the anteromedial region of the superior facet and posterolateral portion of the uncinate process (Sohn et al., 2004). Both height and width of the neuroforamina affect its CSA but width reduces with age (Houser et al., 1993) and degenerative changes can cause the nerve to be forced superiorly or inferiorly into the recess of its hourglass shape, especially with movement, leading to nerve root compression (Chang et al., 2017). However, in this study which assessed foraminal width, we did not show a significant association between the degree of stenosis or the location of the nerve root compression with preoperative or postoperative function for either surgical approach.

Compression of the nerve as it passes through the neural foramen may be predominantly anterior, predominantly posterior, or balanced and the structural cause of the compression may vary. Thus, symptomatic patients with radiculopathy most commonly have anterior compression from osteophytes or a soft disc prolapse (Kim et al., 2016) whereas in those with posterior compression it is most commonly from facet joint or ligamental hypertrophy (Sohn et al., 2004). Our results support the findings of Siller et al. (2018) that anterior compression is more common in surgical series, but there is no difference in surgical outcome even in those with pure anterior disease treated with anterior cervical discectomy or cervical foraminotomy.

There are various ways that patients with cervical degenerative disease can be imaged. Oblique cervical spine x-rays demonstrate the bony margins of the cervical foramina and compare favourably with cervical CT scans in assessing neural foraminal dimensions (Doel, 1956; Miller et al., 2011) but standard radiographic imaging has limited use in the diagnosis of cervical radiculopathy (Roberts et al., 2003). CT is helpful in cases where more information regarding the bony anatomy is required but it is unable to image the spinal cord or nerve roots and therefore has little role in the routine investigation of patients with cervical radiculopathy (L. W. Goldman, 2008). CT myelography can demonstrate the anatomy and pathology (Shimauchi-Ohtaki et al., 2022) and may still have a place where MRI is not possible (Song et al., 2009) but it is invasive and expensive.

While CT provides excellent bone definition it is inferior to MRI, which is considered the gold standard when it comes to detailing soft tissues, therefore, the standard imaging used for cervical radiculopathy is MRI. MRI is especially good in the assessment of degenerative changes in the discs due to the loss of water and proteoglycan content which cannot be detected by CT (Miyazaki et al., 2008).

Standard imaging protocols include axial and sagittal T1 and T2 sequences to ensure there is adequate visualisation of the anatomical structures and pathology.

The neural foramen is located anterior to the vertebral canal and at an angle of 45 degrees relative to it in the coronal plane. Due to this orientation sagittal or better, oblique sagittal views, give improved visualisation of the foramina when compared with standard axial views (Goodman et al., 2006). It is notable that this limitation of axial images is well documented in that they do not allow evaluation of the disc and bone contours of the neuroforamina in a single slice due to the anatomical angle the nerve exits the spine. 3D isotropic acquisition with multiplanar reconstruction or oblique sagittal MR images may improve the ability to accurately evaluate the severity and location of any neuroforaminal stenosis (Kintzelé et al., 2018; Barnaure et al., 2022).

There are various specialist MRI sequences that can be performed other than the traditional T1 and T2 weighted imaging. One such sequence is diffusion tensor imaging (DTI). This uses the principles of diffusion weighted imaging (DWI) to look at the movement of water molecules. These molecules will tend to diffuse down axons rather than across them, this asymmetry is termed anisotropy. DTI assesses the magnitude of anisotropy within a 3x3 matrix and computer algorithms can be used to generate tracts that are then usually colour coded (Jellison et al., 2004). Recent literature in the lumbar spine has emphasised the importance of functional imaging using DTI to demonstrate nerve root inflammation in acute sciatica (Bruno et al., 2022). Furthermore the symptoms from herniated cervical discs can be worse than those from cervical osteophytes as chemical mediators are released that cause nerve inflammation (Wong et al., 2014). DTI may provide further diagnostic and predictive information over current standard anatomical MR imaging in patients with acute brachialgia due to nerve root inflammation in the cervical spine. The validity of this should be examined in future research.

This study found that the location and severity of foraminal stenosis as demonstrated on standard anatomical MRI scans is not associated with preoperative or postoperative function irrespective of the surgical approach used. This may be a type II error due to poor imaging of the affected cervical nerve root foramina, therefore we propose that additional research is indicated to investigate this further. It is unknown whether improved anatomical imaging of the foramina with non-orthogonal views or whether using functional imaging techniques such as DTI can demonstrate a significant association between preoperative imaging abnormalities and clinical function or surgical outcome.

The limitations of this study include the relatively small number of posterior cases and the retrospective nature of the research which has resulted in a high exclusion rate. This study excluded 98% of cases which were reviewed, however zero were lost to follow up. It is acknowledged that this can include selection bias, which may inadvertently exclude certain groups from the study population, leading to a sample that is not representative of the target population. This can skew the results and limit the generalisability of the findings. It can also introduce a sampling bias which can disproportionately affect certain demographic groups or characteristics, the resulting sample may not accurately represent the population of interest. To mitigate this the rationale for the exclusion criteria was carefully considered. We have presented transparent exclusion criteria, the numbers assessed and the potential impact of the study's findings.

There was no CT imaging included, MRI can underestimate the degree of bony foraminal stenosis (Kim et al., 2015). Follow up was also short, surgical outcome after 6 weeks does not necessarily reflect surgical outcome after 52 weeks (Thomson et al., 2024). This study examines a real-life cohort, and it reflects the patient population seen at a tertiary neurosurgical referral centre. It must also be noted that the foramina shape and nerve root diameters differ depending on the cervical level. Over 87% of the included cases were those at the most commonly affected region of the cervical spine and the grading systems used are designed to compensate for this variation (Meacock et al., 2023). Nevertheless, the principle finding, which challenges the established literature (M.S. Park et al., 2015; Kim et al., 2016; Siller et al., 2018), is that that the severity and position of foraminal stenosis on preoperative standard anatomical MRI scans may not be clearly associated with clinical function or surgical outcome. This finding has potentially significant clinical implications especially regarding how MRI is used in the diagnosis of this condition.

4.2.5 Conclusions

Despite showing that NDI improves with surgery, the results do not demonstrate an association between any of the radiological measurements or radiological grading systems for cervical neuroforaminal stenosis and either preoperative NDI or change in NDI six weeks after surgery. For those patients with anterior compression, there was no significant difference in outcome between those treated with an Anterior Cervical Discectomy and those treated with a Posterior Cervical Foraminotomy.

Current standard orthogonal axial MR images may not adequately assess the cervical nerve root foramina or predict which surgical approach is indicated. Other imaging approaches for example through oblique sagittal or 3D isotropic acquisition with post-acquisition multiplanar manipulation may better visualise the neural foramina. A longer follow up period and the potential role of advanced MR imaging techniques, such as DTI, in the assessment of patients with brachialgia should also be explored.

5 Diffusion tensor imaging as a predictor of pre-operative function and functional surgical outcome

5.1 Abstract

5.1.1 Background

Cervical radiculopathy is commonly caused by degenerative foraminal stenosis, producing neck pain, brachialgia, and disability. While structural MRI is the standard investigative imaging tool, it provides limited information about the microstructure of spinal nerve roots. Diffusion tensor imaging (DTI) generates proxy measures of nerve 'health' which are sensitive to myelination, axon diameter, fibre density and organisation that may enhance diagnosis and prognostication. This pilot study explored the feasibility of cervical nerve root DTI and its relationship with functional outcomes.

5.1.2 Methods

A prospective single-centre cohort of patients undergoing anterior cervical discectomy (ACD) or posterior cervical foraminotomy (PCF) for single-level radiculopathy was recruited from 13-09-2021 and 16-09-2022. Exclusion criteria included myelopathy, prior cervical surgery, tumour, trauma, multilevel disease, or central canal stenosis. Pre-operative and 6-week post-operative Neck Disability Index (NDI) scores were collected. MRI was performed at 3T using in-house DTI protocols. Regions of interest were placed over symptomatic and contralateral nerve roots and hemi-cords. Extracted metrics included fractional anisotropy (FA), mean diffusivity (MD), quantitative anisotropy (QA), restricted diffusion imaging (RDI) and isotropic value (ISO). Pearson correlations and paired t-tests were applied.

5.1.3 Results

50 patients were screened, 11 were recruited and 6 analysed that underwent surgery (3 ACD, 3 PCF). No statistically significant correlations were observed between DTI metrics and NDI, or between symptomatic and contralateral measurements. However, QA and ISO showed strong negative trends with both pre-operative NDI and change in NDI (correlation coefficients –0.7).

5.1.4 Conclusions

Quantitative DTI of cervical nerve roots is technically feasible and may provide additional clinically meaningful information about morphologically normal spinal nerves in symptomatic patients. Although the sample size was limited, this pilot study highlights promising trends that support larger, multicentre studies to validate DTI as a diagnostic and prognostic tool in cervical radiculopathy.

5.2 Manuscript

5.2.1 Introduction

The natural aging process induces degenerative alterations in the spine, such as disc prolapse, osteophyte formation, facet joint hypertrophy, and ligament thickening. These degenerative changes can result in the stenosis of the nerve root foramina, through which the cervical nerve roots pass, leading to cervical foraminal stenosis. This stenosis often causes cervical nerve root compression (Rao, 2002). Cervical nerve root compression typically manifests as cervical radiculopathy, characterised by neck pain, radiating arm pain (brachialgia), and referred neurological symptoms in the arm or hand. In severe cases, cervical radiculopathy can lead to loss of upper limb function and significant disability. Although it can occur at any age, it predominantly affects individuals over 40 years old (Tumialán et al., 2010; Alvin et al., 2016). In the UK, brachialgia is estimated to affect around 110,000 patients each year. Although approximately 75% improve over several months with conservative treatment, a proportion of those with persistent symptoms go on to require further imaging assessment and some may ultimately undergo surgery (Carette, 2005; Caridi et al., 2011).

The most common surgical procedures used to treat brachialgia are anterior cervical discectomy (ACD) and posterior cervical foraminotomy (PCF). The choice between them depends on surgeon and patient preferences, complication risks, patient factors, and pre-operative MRI findings (Malcolm, 2002). Due to the varying morphology of foraminal stenosis among patients (Lee et al., 2017), it is unclear if one procedure is superior for specific types or locations of nerve root compression (Yousem et al., 1991). The existing literature has not sufficiently explored the potential correlation between the location, severity, or length of nerve root compression and the clinical symptoms or functional outcomes of surgery.

Diagnosing and evaluating cervical radiculopathy can be challenging due to the complexity of the cervical spine's anatomy and the variability of symptoms. Conventional imaging techniques, such as MRI and CT, are often used but may not provide detailed information about nerve integrity. Diffusion tensor imaging (DTI) provides objective information about the microstructure of nerves. DTI metrics are sensitive to axon type, diameter, myelination, density and organisation (Heckel et al., 2015; Andersson et al., 2018; Friedrich et al., 2020). DTI can identify root compression in the cervical and lumbosacral (Liang et al., 2021; Wang et al., 2022) region due to discopathy, as well as peripheral nerve compression at various anatomical sites including the carpal tunnel (Rojoa et al., 2021) and cubital tunnel (K. et al., 2010; Altun et al., 2013; Breitenseher Gottfried; Hold, Alina; Berzaczy, Dominik; Nemec, Stefan F.; Sycha, Thomas; Weber, Michael; Prayer, Daniela; Kasprian, Gregor, 2015; Ho et al., 2018; T. et al., 2020; S.-Y. et al., 2020).

Fractional anisotropy (FA) is one of the most reported parameters due to its ability to reflect the degree of directional dependence of water diffusion. It has been used as a biomarker of white matter integrity, but its use can be limited in regions of complex fibre architecture such as the cervical neuroforamina. Mean diffusivity (MD) measures the overall degree of diffusion and can be used to help detect pathological changes such as oedema or axonal loss but less so in distinguishing between different aetiologies. Quantitative anisotropy (QA) has been introduced as an additional measure of directional diffusion which is less affected by crossing fibres and free water contamination. This could make it particularly valuable for evaluating the exiting cervical nerve roots (Alexander et al., 2007). Restricted diffusion imaging (RDI) provides an estimate of restricted water movement within axonal structures and may offer potential advantages in detecting early or subtle changes not apparent on other DTI metrics (Yeh et al., 2017). Isotropic value (ISO) quantifies the proportion of non-directional diffusion, helping to separate changes related to oedema or cerebrospinal fluid from those due to true structural compromise (Yeh et al., 2013). These measures together may provide a potential means of identifying early or subclinical nerve injury, improving diagnostic accuracy and offering a valuable aide for monitoring disease progression or guiding surgical decision-making in cervical radiculopathy (Chen et al., 2014). By providing quantitative measures of nerve integrity, DTI may be able to offer a more precise assessment of the extent of nerve damage. This quantification can be particularly useful in cases where traditional imaging shows minimal structural abnormalities, but the patient presents with significant symptoms. Taken together, these measures provide a more subtle assessment of nerve root integrity (Wade et al., 2023). The DTI metrics were selected a priori to include those most appropriate for the neuroforamina. FA and MD were included as established tensor-derived reference measures, while QA, RDI and ISO were additionally explored because they may be more informative in anatomically complex regions such as the cervical neuroforamina (Alexander et al., 2007; Yeh et al., 2013; Yeh et al., 2017).

The Neck Disability Index (NDI) is a widely utilised and well-validated instrument for evaluating self-reported functional disability in patients suffering from neck pain and brachialgia. Each of its ten items is scored from zero to five, with a total possible score of 50 that is subsequently converted to a scale out of 100 (Cleland et al., 2006; Young et al., 2009; Young et al., 2010). The NDI has been employed in over 300 publications within both clinical and research contexts to quantify this prevalent issue and is recommended as an appropriate outcome measure for clinical trials in this patient cohort (Rodine and Vernon, 2012). The index quantifies subjective symptoms and impairments related to activities of daily living or discretionary activities (Wainner et al., 2003). Multiple studies have investigated the minimally important clinical difference (MCID) on the NDI (Westaway et al., 1998; Riddle and Stratford, 1998; Stratford, 1999; Cleland et al., 2008; Young et al., 2009). Notably, a study by Stratford (1999) with the highest reliability in the literature reported a change of 5 out of 50 points (equivalent to 10%) as the MCID, which would justify a recommendation for surgical intervention (Stratford, 1999; Young et al., 2010).

The aims of this pilot project were to:

1. Explore the correlation between DTI measurements in symptomatic spinal nerve roots and NDI
2. Compare DTI measurements of symptomatic and contralateral asymptomatic spinal nerves
3. Determine possible differences between DTI measurements of the hemi-cord on the side of symptomatic nerve and contralateral hemi-cord

5.2.2 Materials and methods

This prospective cohort study was from a single institution in England. The study was assessed by the trust research governance service and was found to require formal Health Research Authority (HRA) and NHS Research Ethics Committee approval. This was granted under REC reference 20/SS/0096 and IRAS project ID 285222.

5.2.2.1 Study population

A database was created of surgical patients who were on the elective waiting list to have an ACD or PCF for cervical radiculopathy between 13-09-2021 and 16-09-2022.

The inclusion criteria comprised: planned surgical intervention (ACD or PCF), age 18 years and over and preoperative brachialgia. The exclusion criteria comprised: cervical myelopathy, previous cervical surgery, evidence of suspected or histologically proven tumour, multiple level pathology, trauma, central canal stenosis and contraindications to MRI.

The target sample size of 12 patients was chosen in line with the “12 per group” rule of thumb for pilot studies, which provides a pragmatic balance between feasibility and the need for reliable preliminary data (Julious, 2005). Recruiting 12 participants allows for estimation of key parameters with sufficient precision to inform the design of a larger definitive trial, while avoiding unnecessary over-recruitment at this exploratory stage.

5.2.2.2 Clinical outcome data

Clinical outcome in the form of NDI data was collected from patients with symptoms of radiculopathy by a neurosurgical medical professional. Only those patients with a single cervical level and symptoms that correlated with this level were chosen in this study. NDI was measured preoperatively and six weeks postoperatively.

5.2.2.3 MRI acquisition and processing

Imaging was performed at a field strength of 3 Tesla (3T) using a MAGNETOM Prisma (Siemens Healthcare, Erlangen, Germany). Participants were scanned supine using a 64-channel head & neck coil. DTI was acquired using single-shot echo-planar imaging with the following parameters: 50 contiguous 2.5 mm axial slices, in-plane resolution 2·5mm^2, field-of-view (FoV) 305 × 305 mm (matrix size 122 × 122), a TrueForm B1 shim, 64 non-collinear monopolar diffusion-encoding gradients, b-value 1000 s/mm^2, 4 interleaved non-DW (b0) images, TE 68 ms, TR 6500 ms, GRAPPA 2, 6/8 partial Fourier, receiver bandwidth 2275 Hz, distortion correction off and strong fat saturation. Four repetitions (256 diffusion-weighted images and 16 interleaved b0s) were acquired over 24 min. DICOMS were exported, converted to nifit using dcm2niix (Li et al., 2016) and denoised by MP-PCA (Veraart et al., 2016) in MRtrix3 (Tournier et al., 2019). We did not correct for distortions induced by susceptibility or eddy-currents because this remains a globally contentious issue (Tax et al., 2022; Veraart, 2022) and common approaches change diffusion parameter estimates (Wade et al., 2024). Denoised data were imported to DSI Studio (Yeh, 2021). Diffusion was quantified using restricted diffusion imaging (Yeh et al., 2017) and reconstructed using Generalised Q-Sampling Imaging (Fang-Cheng Yeh et al., 2010), with a sampling length ratio of 1·25. Structural MR imaging of the C-Spine was also acquired (Axial and Sagittal T2) as per the parameters in Table 3-2 hospital 1 with the exception of the field strength being 3T (Meacock et al., 2024).

5.2.2.4 Extraction of diffusion related metrics

To extract metrics from the spinal nerve roots, region of interests (ROI) were manually drawn to include the contents of the neuroforamina. It must be noted that the segmental mixed spinal nerve, nerve root ganglion, meningeal sheath and meningeal nerves as well as spinal radicular arteries and epidural veins connecting internal and external venous plexuses were all contained within the ROI. The neuroforamina has three distinct zones (Figure 1-5, p25) which are the medial (related to the pedicle), middle (related to the vertebral artery) and lateral zones which were all included bilaterally for C2 to C7. The ROI was limited to one voxel in one slice (2·5 × 2·5 × 2·5 mm, i.e. 6·25 mm^3) per root. The ROI was centred over the middle of the cross-section of the nerve to avoid partial volume effects (Wade et al., 2023).

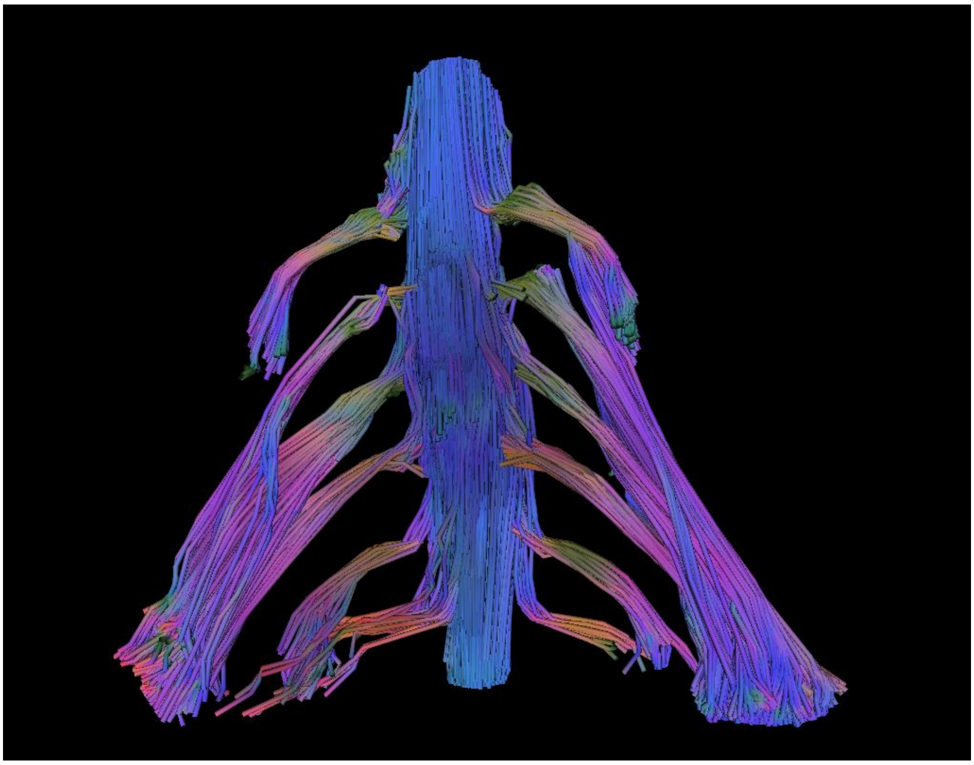


Figure 5-1 DTI tractography of C2-C7 nerve roots are seen exiting the spinal cord for patient 1
Standard colour coding based on the direction of fibres (Blue=superior-inferior, Red=left-right, Green=anterior-posterior)

We hypothesised that the hemi-cord from which the symptomatic nerves originated may show abnormal DTI measurements and each hemi-cord was bisected along the anterior and posterior median sulcus and the ROI was limited to one slice for C2 to C7. From each ROI we extracted the following 'ROI-based' parameters: QA, MD, ISO, RDI and FA.

5.2.2.5 Statistical analysis

DTI data was collected from a group of patients, involving measurements on the affected nerve, and for all other nerves bilaterally. The analysis examined the associations between these measurements and clinical outcome (as measured by NDI) and examined the differences between the affected nerves, and the matching unaffected nerves.

The first set of analyses examined the association between the DTI measurements and measurements of the NDI score. All variables were continuous and were analysed using Pearson correlation. A second set of analyses examined the differences between the DTI measurements made on the affected side values, and the equivalent matching value on the other side. As there were two measurements from each patient, the analyses were performed using the paired t-test.

5.2.3 Results

From the 50 patients screened 11 (22%) patients were recruited and 39 excluded.

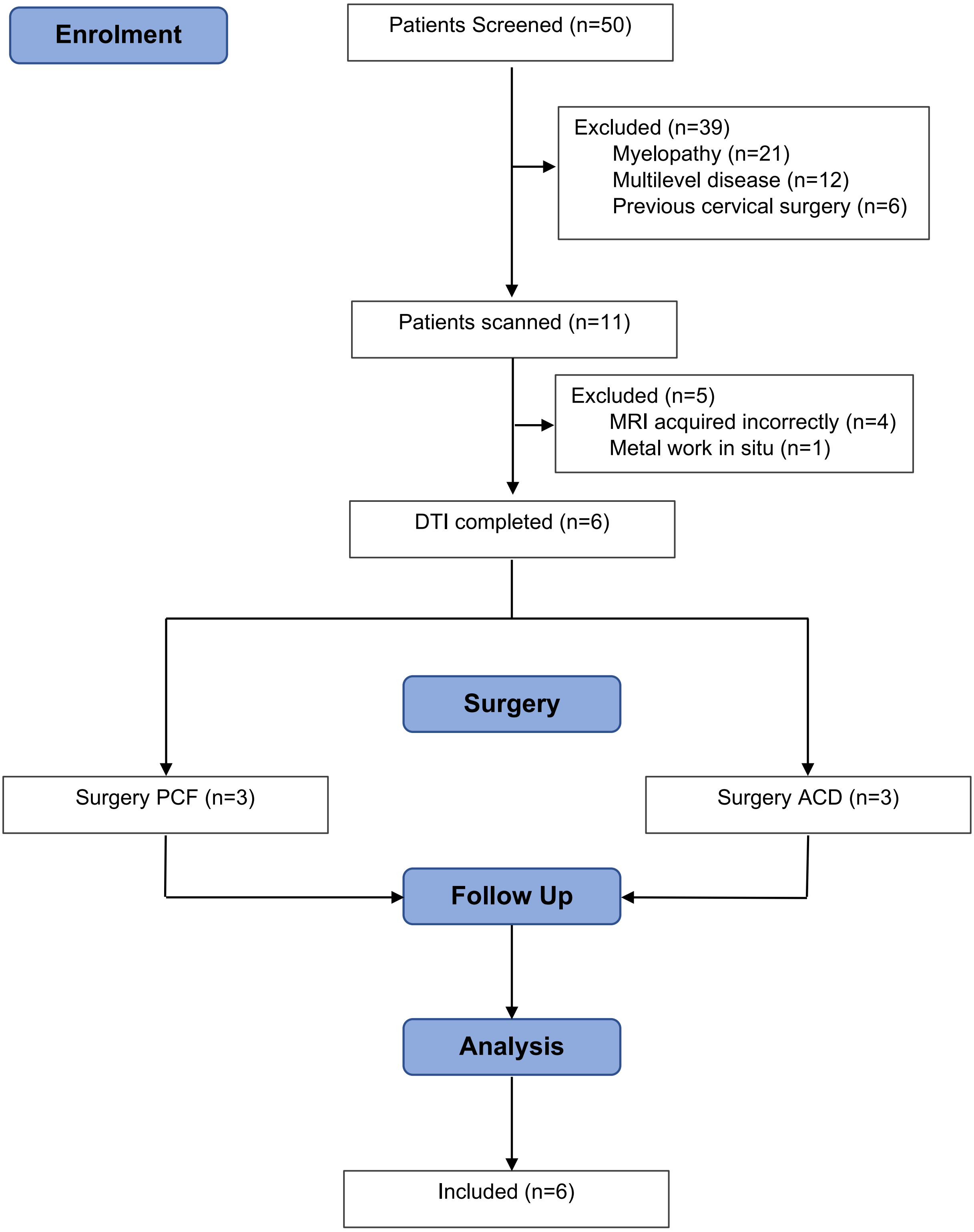


Figure 5-2 Flow diagram of patient inclusion

The reasons for exclusion were, myelopathy 21 (42%) patients, multilevel disease 12 (24%) patients and previous cervical surgery 6 (12%) patients. Five were not included in the DTI analysis due to four having DTI sequence failures due to radiographer operator error and one had metal artifact rendering the results uninterpretable. For the remaining six included, three (50%) patients had a posterior cervical foraminotomy and three (50%) had an anterior cervical discectomy (Figure 5-2).

5.2.3.1 Baseline data

Patient baseline and operative variables are shown in Table 5-1. The patients had a mean [±SD] age of 58 years [±10.3]. Three (50%) were female. None of the cohort smoked.

Each recruit had at least one comorbidity. One had two comorbidities (which were hypercholesterolemia and hypertension) and two had three comorbidities (which were high alcohol intake, transient ischaemic attack, renal cell carcinoma, asthma, COPD and fibromyalgia).

The American Society of Anaesthesiology (ASA) grade (Doyle et al., 2023) was recorded as grade 1 in 100% of patients. 100% of the operations had a consultant as primary or secondary surgeon. The operative level was either C5/C6 n=3 (50%) or C6/C7 n=3 (50%). Four (67%) operations were for right sided and two (33%) for left sided disease.

Variable		Number
Mean age [SD] in years		58 [10.3]
Gender	Male	3
	Female	3
Smoker	Yes	0
	No	6
American Society of Anaesthesiology (ASA) grade	1	6
	2	0
	3	0
	4	0
	5	0
Comorbidities	Transient ischaemic attack	1
	Hypertension	1
	Hypercholesterolaemia	1
	Renal cell carcinoma	1
	Asthma	1
	COPD	1
	Fibromyalgia	1
	Ischaemic heart disease	1
	Epilepsy	1
	Thyroidectomy	1
Side	Left	2
	Right	4
Operative level	C2 / C3	0
	C3 / C4	0
	C4 / C5	0
	C5 / C6	3
	C6 / C7	3
	C7 / T1	0

Table 5-1 Patient demographics

5.2.3.2 Comparison of FA values by cervical level

Descriptive FA values by cervical level are summarised in Table 5-2. The mean FA values showed some variation between levels and between right and left sided measurements. The lowest mean FA was observed at C2, while the highest mean values were seen at C5 followed by C4.

Location	FA Mean ± SD		
	Right	Left	Mean
C2	0.24 ± 0.14	0.24 ± 0.11	0.24 ± 0.12
C3	0.28 ± 0.11	0.30 ± 0.07	0.29 ± 0.08
C4	0.36 ± 0.06	0.32 ± 0.06	0.34 ± 0.03
C5	0.36 ± 0.02	0.35 ± 0.07	0.36 ± 0.04
C6	0.29 ± 0.04	0.36 ± 0.10	0.32 ± 0.06
C7	0.33 ± 0.05	0.26 ± 0.05	0.30 ± 0.04

Table 5-2 Descriptive fractional anisotropy (FA) values by cervical level

5.2.3.3 Associations between affected nerve DTI and NDI scores

This set of analyses examined the association between the DTI measurements and the clinical outcome, as measured by the NDI score. Associations with the pre-op and post-op NDI scores were examined, as were associations between the change in NDI from pre to post-op. A summary of the results is reported in Table 5-3. The figures presented are the correlation coefficients, along with associated p-values indicating the significance of the associations. A "good" correlation coefficient is generally considered to be above 0.7 (or below -0.7) for strong positive (or negative) relationships, while values below 0.3 (or above -0.3) indicate weak or no linear correlation.

There were no statistically significant associations between any of the DTI measurements and any of the NDI measurements.

Although the correlations did not reach statistical significance, there was a trend towards a negative association between QA values and both pre-operative NDI and

NDI change (correlation coefficients around –0.7). This suggests that higher QA values may be related to lower pre-operative NDI scores and smaller changes from pre- to post-operative status. The relationship between post-operative NDI values and QA appeared weaker.

DTI variable	NDI Pre		NDI Post		NDI Change	
	Correlation	P-value	Correlation	P-value	Correlation	P-value
FA	0.12	0.82	-0.22	0.68	0.20	0.70
QA	-0.71	0.12	0.40	0.43	-0.73	0.10
MD	-0.46	0.36	0.26	0.62	-0.47	0.35
ISO	-0.59	0.21	0.24	0.63	-0.57	0.24
RDI	-0.60	0.21	0.27	0.61	-0.58	0.22

Table 5-3 Associations between affected nerve DTI values and NDI scores

There were similar moderate negative correlations with pre-op NDI and change in NDI for ISO. The correlations were slightly smaller here (compared to QA), around -0.58. These suggest that higher ISO values were associated with lower pre-op NDI and a lower change in NDI from pre-op to post-op.

5.2.3.4 Differences between affected and matching (unaffected) DTI values

A second set of analyses were performed to examine the differences between the affected side values, and the equivalent matching value on the other side. Analyses were performed for the nerve measurements and the hemi-cord measurements.

The analysis results are summarised in Table 5-4. The first figures reported are the mean and standard deviation values for both the symptomatic and asymptomatic sides (cervical levels have been grouped). The mean difference between sides is shown, along with corresponding confidence intervals. These are calculated as value for affected side minus value for unaffected side. P-values, as indicators of significant difference between sides, are shown in the final column.

Measurement	DTI variable	Symptomatic Mean ± SD	Asymptomatic Mean ± SD	Difference Mean (95% CI)	p
Nerve	FA	0.31 ± 0.06	0.32 ± 0.11	-0.01 (-0.15, 0.12)	0.80
	QA	0.13 ± 0.13	0.10 ± 0.08	0.03 (-0.04, 0.11)	0.29
	MD	1.15 ± 0.27	1.25 ± 0.49	-0.10 (-0.80, 0.61)	0.74
	ISO	0.50 ± 0.53	0.34 ± 0.29	0.16 (-0.11, 0.43)	0.18
	RDI	0.27 ± 0.28	0.18 ± 0.15	0.08 (-0.06, 0.22)	0.19
Hemi cord	FA	0.44 ± 0.11	0.44 ± 0.11	0.00 (-0.09, 0.09)	0.92
	QA	0.23 ± 0.18	0.25 ± 0.21	-0.02 (-0.07, 0.03)	0.32
	MD	1.23 ± 0.24	1.28 ± 0.34	-0.05 (-0.47, 0.37)	0.77
	ISO	0.46 ± 0.39	0.48 ± 0.41	-0.03 (-0.12, 0.07)	0.50
	RDI	0.26 ± 0.22	0.28 ± 0.23	-0.02 (-0.07, 0.04)	0.47

Table 5-4 Differences between affected and matching (unaffected) DTI values

There was no statistically significant difference in DTI measurements from the symptomatic side and asymptomatic side. This was the case for both the nerve and hemi-cord measurements.

5.2.4 Discussion

This pilot study aimed to investigate the potential role of DTI in assessing cervical radiculopathy and it sought to:

1. Explore correlations between DTI measurements and NDI scores
2. Compare DTI parameters between symptomatic and contralateral asymptomatic nerves
3. Examine hemi-cord differences

The findings demonstrated that although no statistically significant associations were observed there were notable trends. Negative correlations were identified for QA, ISO and RDI with both pre-operative NDI and change in NDI from pre-operation to post-operation, with correlation coefficients approaching –0.7. This pattern indicates that higher QA values, which reflect greater preservation of microstructural integrity within the affected nerve root, may correspond to lower levels of pre-operation disability and smaller changes in symptoms after surgery. In contrast lower QA values, which suggest more pronounced disruption of directional diffusion, tended to be associated with higher baseline disability and greater postoperative improvement. Similarly, the correlations for ISO and RDI may suggest that these parameters could reflect related but less specific aspects of microstructural compromise. While these did not meet thresholds for statistical significance, the magnitude of the correlations suggests potential clinical relevance that may become apparent in larger studies.

Descriptive FA values also showed some variation by cervical level. Lower mean FA values were seen at C2, with relatively higher values at C4 and C5. This may reflect underlying anatomical or microstructural differences between cervical roots rather than disease-related effects alone. Right-left differences were also observed at some levels, particularly C6 and C7, although given the very small sample these findings should be regarded as descriptive only. Overall, this supports the need for larger studies to define normal level-specific diffusion values before DTI metrics can be interpreted confidently in pathological cohorts.

There were no significant differences were found between symptomatic and asymptomatic sides for either nerve or hemi-cord measurements. It could be possible that bilateral microstructural alterations occur. Alternatively, it would be the relatively small cohort size rather than an absence of true effect.

Importantly, this study demonstrates proof of concept that quantitative assessment of the cervical nerve roots using DTI is feasible, not only for FA but also for other measures such as QA, RDI and ISO. This is technically challenging given the very small CSA of the cervical nerve roots (typically 2–3 mm in diameter), their anatomical complexity and susceptibility to motion artefacts. Successful extraction of multiple diffusion metrics from these structures indicates that with optimised acquisition protocols, quantitative imaging of cervical nerve roots is achievable. This builds on previous work showing the utility of DTI in the roots of the brachial plexus as biomarkers of both disease within the CNS (Wade et al., 2025) and periphery (Wade et al., 2023) and supports further evaluation in larger studies.

Attrition in this study is also important to discuss, as five of the 11 recruited patients were not included in the DTI analysis. This was primarily due to operator-related sequence failures related to radiographer changes between runs, together with one case of metal artefact. This highlights the importance of operator consistency and the practical challenges for centres considering similar work. In future multi-centre studies, data loss from poor image acquisition could be reduced by using a standardised DTI protocol, pre-study radiographer training, written acquisition checklists and central quality assurance. Initial pilot scans from each site should be centrally reviewed before full recruitment begins, so that technical problems can be identified and corrected early. Regular feedback to sites, real-time image quality checks and repeat acquisition where feasible would further reduce operator-related errors and improve dataset completeness. Patient movement, sequence optimisation and operator experience remain critical for ensuring interpretable datasets. Reporting these challenges may assist future research teams in refining acquisition protocols and minimising data loss. Long-term longitudinal studies, such as those suggested by the FORVAD study (Thomson et al., 2024), are essential for understanding the progression and natural history of cervical radiculopathy. Large-scale clinical trials utilising standardised DTI protocols will be critical in validating the clinical applicability of DTI, establishing evidence-based guidelines and clarifying which patient scenarios most benefit from DTI.

Several limitations must be acknowledged. The small sample size (n=6) substantially reduced statistical interpretation, meaning that large effect sizes would have been required to achieve significance. As such, negative findings must be interpreted with caution. In addition, this was a single-centre feasibility study with potential operator dependency in both imaging acquisition and ROI placement. There was also a restricted size of database used to recruit patients (n=50). Together, these factors limit generalisability of the findings.

5.2.5 Conclusions

This pilot study provides early evidence that quantitative DTI of cervical nerve roots is feasible. It can generate meaningful diffusion metrics beyond conventional FA. Although no statistically significant associations were found with functional outcomes, the observed trends suggest potential clinical relevance that warrants further investigation. Future studies should utilise larger multi-centre cohorts to increase sample size and diversity. Standardised acquisition and post-processing protocols to reduce variability. Longitudinal follow-up to better establish the clinical utility of DTI in cervical radiculopathy and how they relate to natural history of the disease. With ongoing advances in MRI technology, DTI has the potential to contribute to improved diagnostic accuracy, prognostication and surgical planning in this patient group.

6 Discussion

This thesis provides an in-depth analysis of the radiological assessment of cervical neuroforaminal stenosis which is a common and debilitating spinal condition. Cervical neuroforaminal stenosis occurs when degenerative changes in the spine lead to narrowing of the cervical nerve root canals causing nerve root compression. Patients typically report neck pain, brachialgia and impaired function. When conservative treatment fails, surgery is indicated. Effective diagnosis, evaluation and grading of stenosis severity are important for guiding clinical management and surgical decision making.

This thesis had four objectives:

1. Systematically review the current grading systems for cervical foraminal stenosis
2. Assess current and novel grading systems and quantitative measures in a cohort of patients with cervical spondylosis
3. Investigate which morphological features of cervical foraminal stenosis in patients with cervical radiculopathy correlated best with pre-operative and post-operative surgical outcome following ACD or PCF
4. Explore DTI metrics within a prospective cohort of patients with cervical spondylosis and how these relate to functional disability as measured with NDI

These were addressed sequentially through the included studies. The work progressed from defining the problem to challenging current concepts and exploring possible solutions. I will outline a summary of how these were achieved before exploring in further depth the current findings and future areas of interest.

The initial published systematic review established the available evidence base by critically appraising all published grading systems for cervical foraminal stenosis. The systematic review identified key existing methods including the Kim, modified Kim and Park systems. It also exposed several fundamental limitations including inconsistent imaging protocols, reliance on subjective descriptors and a lack of validation against patient-centred outcomes. Importantly, it highlighted that even the most widely cited systems had limited external validation and that their clinical value was uncertain. By explicitly highlighting these gaps in this area, the systematic review created a strong justification for empirical studies to test reliability and prognostic value in real world surgical cohorts (Meacock et al., 2021).

The next published reliability study directly addressed the assumption that established grading systems can be applied consistently in clinical practice. While intra-rater agreement was good, the strikingly poor inter-rater agreement (κ = 0.01–0.08) suggests that these systems are vulnerable to interpretive variation between the clinicians making the measurements. This finding is particularly important because it implies that, without standardisation and clearer operational definitions, reported grades may not reliably reflect the patient's pathological severity. Clinically, this undermines the value of these systems for surgical decision making and methodologically, it limits their utility in multicentre trials (Meacock et al., 2023).

The third published study extended this critique by asking whether morphological measurements or existing grading systems could predict functional disability or surgical benefit, as measured using NDI. The results demonstrated that despite surgery producing statistically significant improvements in NDI, no radiological measure or grade demonstrated a meaningful association with baseline function or change in outcome. This challenges a prevailing clinical belief that more severe radiological compression equates to worse symptoms or better surgical response. The absence of predictive value reinforces the view that current imaging techniques and grading systems capture anatomical narrowing but fail to reflect the true physiological or microstructural changes of the compressed nerve root, the factor likely to determine symptom severity and recovery potential (Meacock et al., 2024).

The final objective assessing DTI, follows on from the findings in the previous studies. It stands to reason that if current anatomical grading systems are unreliable between raters and lack predictive validity, the field must explore alternative imaging biomarkers. DTI offers the prospect of quantifying axonal integrity and microstructural changes within the nerve root. This could potentially close the gap between image appearance and functional impairment. While the application of DTI to the cervical neuroforamina remains technically challenging, this thesis positions DTI as a promising avenue for future work aimed at delivering reproducible, objective and clinically relevant imaging metrics.

Taken together this thesis provides a critical reappraisal of how cervical foraminal stenosis is assessed. It demonstrates that the limitations are not merely technical but conceptual. Grading systems currently grounded in static anatomical narrowing cannot, on their own, capture the complex pathophysiology of nerve compression. By first documenting these shortcomings and then pointing towards advanced imaging solutions, this work helps to work towards a necessary shift, from purely morphological grading to integrated, quantitative and biologically meaningful assessment of neuroforaminal stenosis.

6.1 Comparative evaluation of radiological techniques in cervical spine imaging

Imaging is central to the diagnosis, classification and surgical planning of cervical neuroforaminal stenosis. Each modality offers distinct advantages and disadvantages. These include its ability to visualise the neuroforamina, quantify narrowing and correlate with clinical symptoms. The major techniques include plain film radiography, CT, MRI and oblique imaging views. These can be either as dedicated acquisitions or reconstructions from volumetric datasets (Meacock et al., 2021).

6.1.1 Plain film radiography

Plain radiography is a two dimensional, rapid, cost-effective and widely available first-line tool. It can be used for the assessment of gross cervical spine pathology, alignment abnormalities and degenerative changes. Its role in the evaluation of foraminal stenosis is inherently limited by its inability to depict the foramina directly. It struggles to evaluate soft tissues, subtle bony abnormalities and the interpretability is confounded by overlapping structures. It does have some uses in dynamic imaging to evaluate stability, however when foraminal pathology is suspected, plain radiographs should be supplemented with more advanced imaging modalities (Duane et al., 2010). This includes most commonly MRI for comprehensive soft tissue assessment and CT when detailed evaluation of bony anatomy is required for accurate diagnosis and surgical planning (Sabiston et al., 1987; Simpson et al., 2008; Peene et al., 2023).

6.1.2 Computed tomography

CT provides high spatial resolution for bony structures and is particularly effective in assessing bony contributors to cervical foraminal stenosis, including osteophytes, facet joint hypertrophy and congenital narrowing (Park et al., 2013). Modern CT allows thin-slice acquisition with high-quality multiplanar reconstructions, including sagittal oblique reformats aligned to the axis of the neural foramina. This can enable a more accurate depiction of the true CSA. Such reconstructions can be especially valuable for pre-operative planning, where precise knowledge of the extent and orientation of bony encroachment can help inform surgical approach (Schell et al., 2017; Ozaki et al., 2020).

CT has several advantages over plain radiography including, elimination of overlapping anatomical structures, accurate three-dimensional representation and the ability to quantify bony foraminal dimensions objectively. However, it is limited in the assessment of soft tissues such as the intervertebral disc, ligamentum flavum and nerve roots, all of which can contribute to foraminal narrowing (Meacock et al., 2021). CT also involves ionising radiation exposure, which may be a consideration in younger patients or in serial imaging scenarios. CT is often used as an adjunct to MRI when there is diagnostic uncertainty or when the surgical objective requires detailed bone visualisation (American College of Radiology, 2012).

6.1.3 Magnetic resonance imaging

MRI is the gold standard for comprehensive evaluation of cervical foraminal stenosis due to its superior soft tissue contrast and ability to visualise the disc and ligamentous structures without radiation exposure (Bartlett et al., 1998). Standard protocols typically include sagittal and axial T2-weighted sequences, with axial images used to assess the degree of foraminal narrowing and visualise nerve root compression directly (Kim et al., 2017). MRI can also demonstrate secondary changes such as cord signal alteration, which may influence surgical decision-making.

Despite these advantages, MRI is not without limitations. Axial images are usually acquired orthogonal to the spinal cord rather than parallel to the axis of the neuroforamina, potentially resulting in under or overestimation of stenosis (Park et al., 2013). Signal can also be affected by patient motion, artefacts and variations in imaging protocol between centres. Furthermore, while MRI can demonstrate the presence of nerve root compression, current grading systems often rely on subjective interpretation and their correlation with clinical outcomes is inconsistent (Meacock et al., 2020; Meacock et al., 2024).

6.1.4 Oblique imaging views

Oblique imaging techniques can either be directly acquired or reconstructed from three-dimensional datasets which align the imaging plane to the true course of the neuroforamina, allowing visualisation of the entire foraminal canal in profile (Park et al., 2013). This orientation improves the ability to identify focal narrowing, distinguish between anterior and posterior compression and appreciate the longitudinal extent of stenosis (Schell et al., 2017).

Historically, oblique plain film radiographs have been used, but with the advent of CT and MRI this was transitioned towards cross-sectional modalities (Ruiz Santiago et al., 2010). In CT, sagittal oblique reconstructions from volumetric data can be readily performed and have been used to evaluate the neuroforamina (Oshina et al., 2018). In MRI, oblique sagittal T2-weighted acquisitions or reconstructions offer detailed assessment of both soft tissue and to a less extent bony components. However, oblique MRI is not yet standardised in routine clinical protocols. In my systematic review it was found that non-standard oblique views were used in around half of the included studies, indicating variable adoption across centres (Meacock et al., 2021). Barriers to utilising this imaging method include additional scan time and protocol complexity. There is also a requirement for isotropic acquisition, which is not universally available. Nevertheless, when performed, oblique views have been shown to improve inter-rater agreement and may enhance correlation with clinical symptoms compared to conventional axial and sagittal sequences (Park et al., 2014).

6.1.5 Diffusion tensor imaging

DTI offers several potential advantages in the assessment of neuroforaminal stenosis. It can provide quantitative insight into the microstructural integrity of the cervical nerve roots. While conventional MRI predominantly depicts the anatomical extent of neuroforaminal narrowing, DTI takes this a step further by evaluating the physiological consequences of compression at a microstructural level (O’Donnell and Westin, 2011).

Within the diffusion metrics, FA represents the degree of directional water diffusion and can serve as an indirect marker of axonal organisation and fibre coherence. MD measures the overall magnitude of diffusion and can help identify areas of oedema or loss of tissue integrity. QA is less affected by noise, crossing fibres or free water and may therefore more accurately reflect preserved nerve fibre integrity. RDI estimates the proportion of restricted intracellular water motion and has been proposed as a proxy measure of axonal density. ISO is a measure of the proportion of non-directional diffusion and may correspond to extracellular fluid accumulation or tissue disorganisation. Together these parameters may provide a means of identifying subtle or subclinical nerve injury not apparent on structural imaging (Alexander et al., 2007; O'Donnell and Westin, 2011; Yeh et al., 2013).

6.2 Grading systems

6.2.1 Existing grading systems described in the literature

In the first section of this thesis, we reviewed radiological grading systems for cervical foraminal stenosis through the systematic review (Meacock et al., 2021). The review identified various grading systems used in clinical practice, primarily the Kim, modified Kim, Siller and Park systems. These grading methodologies categorise the severity of stenosis using MRI. The review uncovered substantial inconsistencies in grading approaches, primarily due to reliance on subjective terminology such as "minor," "moderate" or "severe". The absence of standardised criteria for grading neuroforaminal stenosis leads to significant inter-observer variability. Most existing grading systems lack validation against clinical and surgical outcomes reducing their practical utility (Meacock et al., 2023).

The risk of bias in the systematic review was assessed qualitatively at study level, focusing on study design, clarity of eligibility criteria, observer methodology and reporting of statistical analysis. Owing to the heterogeneity of the included studies, no single formal risk-of-bias tool was applied. Instead, bias was judged narratively across the evidence base, allowing comparison between studies with differing designs, imaging modalities, grading methods and validation strategies.

The complexity of each grading system and the extent of testing were assigned pragmatically during data extraction and were not based on a formal validated scoring instrument. Complexity reflected the number of grading steps, measurements, imaging planes and morphological features required by each system. The extent of testing reflected the degree of validation reported, including inter-rater or intra-rater agreement, comparison across observers or modalities, and correlation with clinical symptoms or surgical outcomes. These categories were used to provide a comparative overview of the maturity and clinical applicability of the published grading approaches.

6.2.2 Emerging grading research following the systematic review

Since the completion of the systematic review, research into cervical foraminal stenosis has progressed. There have been several studies refining existing systems and introducing innovative quantitative and imaging-based techniques. These approaches range from traditional categorical classifications to volumetric and functional measures. This reflects a push towards improving diagnostic accuracy, inter-observer consistency and clinical relevance. Collectively the studies below published since my systematic review highlight both the progress and remaining gaps in the assessment of cervical foraminal stenosis.

Costello et al. (2023) undertook a retrospective analysis of 40 patients with baseline and follow-up cervical MRI examinations. These were graded independently by three radiologists for interval changes in neuroforaminal stenosis. Using a simple three-point scale (increased, decreased, unchanged), the study achieved strong inter-observer agreement (κ = 0.78–0.94), demonstrating the value of structured, interval-change reporting in follow-up assessments.

Barnaure et al. (2022) retrospectively compared a sagittal oblique 2D MRI sequence with a 3D MRI sequence in 60 patients. Both provided high visibility of foraminal structures, although the 2D sequence was marginally better at depicting foraminal contents. The 3D sequence offered comparable stenosis grading and allowed for multiplanar reformatting capabilities, potentially improving workflow flexibility.

Mizouchi et al. (2020) used dynamic flexion–extension CT to create 3D reconstructions of the cervical foramen. It identified the central portion as the narrowest region, which further constricted in extension. This method provides valuable guidance for determining the optimal extent of surgical resection balancing decompression with preservation of stability.

Coudert et al. (2022) performed volumetric CT measurements of foraminal height, width and volume in symptomatic versus asymptomatic individuals. It found significantly reduced dimensions, particularly in the upper and medial foraminal regions, in the symptomatic cohort. This anatomical insight possibly supports more targeted decompression strategies.

Enomoto et al. (2022) combined two techniques, the first MR neurography, allows nerves to be visualised in detail by suppressing background signals from surrounding tissues. This can help to identify changes such as swelling or compression that may not be apparent on conventional MRI. The second T2 mapping, provides a quantitative measure of tissue microstructure which can highlight pathological changes such as oedema, demyelination or inflammation. These together were used to assess cervical radiculopathy which demonstrated significantly prolonged T2 relaxation times in symptomatic nerve roots when compared with the contralateral side. This quantitative biomarker shows promise as an objective tool for evaluating nerve involvement to support diagnosis and surgical planning.

Razzouk et al. (2024) analysed CT data from 1,000 patients, providing reference values for foraminal width, height and area. These measurements were taken across cervical levels and stratified by sex and race. Males generally had larger foraminal areas, while females exhibited wider foraminal widths. These normative datasets can help distinguish between physiological variation and pathological narrowing.

Seo et al. (2023) revisited the Lee grading system. It demonstrated reproducibility and clinical usefulness of this system in assessing stenosis from mild to severe. The authors supported the continued role of simple, standardised grading systems for facilitating consistent communication.

Wahezi et al. (2022) demonstrated improved diagnostic accuracy when MRI was tailored to patient-specific oblique planes, particularly in anatomically complex cases. While this approach enhances anatomical visualisation, it faces implementation challenges in high-throughput imaging because of additional processing demands, adding work flow burden.

Despite these advances, several methodological and technological constraints limit the generalisability and clinical adoption of the approaches discussed. Enomoto et al. (2022) relied on advanced MR neurography and T2 mapping, requiring high-field (3T)

MRI systems and dedicated neurography protocols that are not universally accessible, restricting routine application in many clinical environments.

Dynamic assessment remains underutilised. Mizouchi et al. (2020) incorporated flexion–extension CT to evaluate positional changes, but this does not capture the full spectrum of possible positions encountered in daily life. Conversely, Razzouk et al. (2024) based their normative dataset entirely on static CT, which cannot reflect the dynamic nature of foraminal narrowing.

Several studies focused on specific structural components without integrating the full range of pathological abnormalities. For example, Coudert et al. (2022) measured only bony structures using CT, excluding soft tissue contributions from other components such as disc protrusion, ligamentous thickening and synovial cysts. These factors which are likely to be clinically significant but would not be visible on CT. It is important to point out that CT is not routinely indicated for initial assessment of cervical radiculopathy, limiting the applicability of such findings to standard clinical pathways.

Lastly, while Wahezi et al. (2022) highlighted the benefit of anatomically aligned MRI planes, this level of individualisation requires additional planning and scanning time. This is likely to not be feasible in busy imaging departments, such as the tertiary neurosurgical centre at which the research in this thesis was based.

Overall, these emerging systems and imaging strategies represent important steps towards more precise, reproducible and clinically relevant assessment of cervical neuroforaminal stenosis. The integration of structural and dynamic parameters offers the potential to bridge the gap between radiological findings and patient outcomes. Limitations relating to technology availability, dynamic assessment and soft tissue evaluation must be addressed before these methods could be widely implemented in routine practice. Future grading systems may benefit from combining high-resolution anatomical imaging with quantitative nerve-specific biomarkers. Normative datasets can improve diagnostic accuracy and prognostic value.

6.2.3 Which grading system was the best?

Building upon the foundation of the systematic review, the thesis moved on to an empirical study (Meacock et al., 2024). This aimed to evaluate the consistency of existing systems including the Kim and modified Kim systems along with additional factors, in a cohort of patients who subsequently underwent cervical surgery. The study involved several experienced clinicians independently grading the severity of cervical neuroforaminal stenosis on axial T2-weighted MRI scans.

No existing system emerged as clearly best across all domains of practicality, reproducibility and clinical relevance. Kim and modified Kim are easy to apply on standard axial MRI, but in my cohort, they showed very poor inter-rater agreement. Park has anatomical advantages through oblique imaging but depends on non-standard views and is less feasible in routine practice. So rather than one system being "best", my thesis suggests that the field has not yet reached a genuinely adequate system

Dynamic imaging (flexion-extension MRI or CT) may add diagnostic information because stenosis can be posture-dependent, however they were not included in this thesis. This was due to their limited availability in routine clinical practice, the lack of standardised protocols and the lack of widely accepted grading systems based on dynamic data. Most existing classification systems are based on static imaging, which enabled comparability with the broader body of literature. As a result, this research has focused on static imaging to maintain methodological consistency and clinical relevance.

Results from this study demonstrated significant variability between different observers (inter-rater consistency), indicating that even among highly trained clinicians, assessment of stenosis severity was inconsistent. When individual observers repeated their assessments (intra-rater consistency), their grading remained relatively stable. These findings highlighted a critical limitation in current grading practices. While clinicians are internally consistent, the lack of inter-rater reliability significantly undermines the uniform application of grading systems across clinical settings.

It is also possible that the grading systems themselves are difficult to apply consistently in routine clinical practice. Although the grading thresholds appear straightforward, they rely on identifying small anatomical landmarks and making measurements on standard axial MRI slices, where slice selection, nerve root orientation and image quality may all affect interpretation. This practical difficulty may have contributed to the poor inter-rater agreement observed in this study and may limit the utility of these grading systems when applied to real-world clinical imaging datasets. In addition, intra-rater agreement was analysed using pooled second-pass data across all raters rather than being reported separately for each rater. While this provided an overall estimate of repeatability, it may have obscured variation in consistency at the individual rater level.

6.2.4 What anatomical sizes have been found from this thesis?

Detailed anatomical analysis (Meacock et al., 2024) revealed interesting variations in cervical anatomy that could influence grading consistency. Specifically, it was identified that foraminal diameter was narrowest at spinal levels C3/C4 and C4/C5 (measured as small as 3.02mm), whereas nerve root diameter was smallest at level C5/C6 (measured as small as 2.26mm).

6.2.5 Most frequent cervical level for degenerative spondylosis

Degenerative changes predominantly affect the mid to lower cervical spine, commonly at the C5/C6 and C6/C7 level. This was most likely due to the biomechanical stresses at these sites. Cervical degenerative disease is however a multi-factorial process, occurring simultaneously in discs, facet joints, uncovertebral joints, ligaments, vertebral endplates and the neural foramina, leading to symptoms (pain, radiculopathy and functional impairment). The anatomical variations outlined likely contribute to the observed inconsistency in radiological assessments, highlighting the importance of considering individual anatomical differences when evaluating patients radiologically. Imaging methods such as volumetric or oblique MRI scans might improve grading accuracy and consistency by better capturing these anatomical complexities.

6.3 Image processing for cervical foraminal evaluation; the opportunities and challenges

Post-acquisition image processing plays an increasingly important role in modern medical imaging. It can offer a range of benefits that can enhance diagnostic accuracy, facilitate surgical planning and improve reproducibility. Edge detection, contrast optimisation and noise reduction can improve the clarity of fine details (D. Li et al., 2025; Melazzini et al., 2025). This can enable better identification of boundaries such as the neuroforamina and nerve root margins. This improved visibility can help enhance subtle features that may be overlooked on raw images, supporting earlier or more precise diagnosis (Maitree et al., 2017; Rorden et al., 2024).

A further strength of processed datasets is that it allows the calculation of objective parameters such as CSA, foraminal width, nerve root diameter. This could also in the context of DTI be various diffusion variables such FA values. These measurements enable reproducible assessments that are less dependent on subjective interpretation, thereby reducing observer variability. Multi-planar and three-dimensional reconstruction techniques extend this capability by allowing the anatomy to be viewed in multiple different orientations such as oblique, sagittal or coronal planes which can align with the natural orientation of structures. This is particularly useful for complex anatomy such as the cervical neuroforamina, where standard axial or sagittal planes may not fully represent the morphology (Schell et al., 2017; Norimoto et al., 2021; Barnaure et al., 2022). Standardised image processing could also reduce inter-observer variation. Semi-automated processing which use reconstruction techniques, could be valuable in multi-centre trials or when serial imaging is required. Furthermore, processed images could be integrated directly into surgical navigation platforms, improving intraoperative localisation, planning and potentially reducing procedural risks (Li and Huang, 2021; Dijkhuis et al., 2024).

Image processing is not without limitations, firstly is the important concern regarding the potential introduction of artefacts. Over-processing can distort images, lead to artificial features, obscure genuine anatomical structures or misrepresent anatomy (Matthees et al., 2025). Importantly, the quality of processed images is strongly dependent on the quality of the original data. The principle of “garbage in, garbage out” states that the quality of the output is based upon its input (Obuchowicz et al., 2025). Poor source information can lead to undesirable outputs caused by patient motion, low magnetic field strength, or suboptimal acquisition protocols cannot be fully rescued by processing and inadequate data may still lead to misleading outputs (Brettle and Carmichael, 2011; Havsteen et al., 2017). Another drawback is the possibility of losing diagnostic information during excessive filtering or compression. Subtle features may be inadvertently removed and for this reason, it is essential that unprocessed raw images remain available for review. Image processing can also be computational resource intensive, with advanced reconstructions such as DTI tractography or volumetric segmentation requiring significantly powerful computers and specialist expertise, potentially increasing reporting time and cost in busy clinical settings (Erickson et al., 2010; Liu et al., 2017).

Variability between software vendors, versions and algorithm settings presents an additional challenge. DSI studio was utilised in this thesis for the DTI, which is an open-source piece of software, but differences between packages could affect quantitative results and reduce reproducibility across institutions. Finally, there is a potential risk of over-reliance on processed images without adequate cross-checking against raw data, which could diminish the radiologist’s direct interpretive skills and increasing the chances of errors occurring (Zussman et al., 2011; Li and Little, 2023).

Image processing has the potential to offer substantial advantages in the visualisation, quantification and reproducibility of cervical spine imaging and could significantly aid surgical planning in the future. Nevertheless, these benefits must be balanced against the risks of artefact introduction, data loss, increased resource demands and variability between platforms. For optimal clinical practice, processed images should be interpreted alongside the original datasets and processing methods should be standardised where possible to maximise reliability and diagnostic value.

6.3.1 Artificial intelligence as a potential tool for reducing processing time and interobserver variability

Artificial intelligence (AI) technologies are being applied in nearly all areas of our lives with the medical imaging field being no exception. AI has been introduced to automate or streamline image post-processing workflows (Najjar, 2023). In the context of cervical foraminal stenosis, AI has the potential to address several of the limitations highlighted in earlier sections. These include the time-intensive nature of manual grading, inter-observer variability and the need for consistent measurement protocols (Meacock et al., 2023).

One key application of AI is in automated segmentation and labelling (Hill et al., 2025). AI models trained on large datasets could identify and segment anatomical structures such as the intervertebral discs and neuroforamina. Such segmentation could form the basis for automated calculation of morphological parameters. These could include important measurements highlighted in this thesis such as the foraminal CSA, minimum diameter and nerve root diameter (Liu et al., 2024). By producing consistent measurements, AI could reduce the variability seen between human raters when applying grading systems such as Kim or modified Kim, as demonstrated in Meacock et al. (2023).

Another area of promise is automated multiplanar reconstruction. Current oblique MRI and CT reconstructions are either manually created or generated using predefined geometric rules, both of which require user intervention (Jeong et al., 2008). AI systems could automatically detect the trajectory of the neural foramina from volumetric data and generate optimal oblique views aligned to the true anatomical axis, without operator input. This would have the benefit of shortening processing time, standardising image orientation between centres and improving reproducibility in both clinical and research settings.

AI-based image enhancement algorithms may also contribute by improving image quality in suboptimal scans. This is likened to how photos taken on smart phones are enhanced by utilising machine learning in programs such as photoshop. Techniques such as super-resolution reconstruction and noise reduction, trained on high-quality reference data, could produce clearer visualisation of small structures such as the cervical nerve root. This might mitigate some of the issues arising from variability in MRI acquisition parameters across institutions, which currently complicates multi-centre comparisons (Chen et al., 2023).

AI has potential for automated grading where AI could be trained to classify foraminal stenosis severity directly from MRI or CT images, either replicating existing grading systems or producing new data-driven categories. More optimistically, AI models could integrate imaging features with clinical data (e.g. symptoms and functional scores) to predict surgical outcomes, potentially addressing the current gap between radiological appearance and patient prognosis identified in this thesis (Hallinan et al., 2021).

Recent advances in AI are beginning to transform clinical imaging workflows. For example, in radiotherapy planning for brain tumours, MRI-only protocols are now feasible, with AI-based CT synthesis algorithms generating the necessary CT datasets for accurate dose mapping. A similar approach in future may be applicable to the cervical spine, where MRI could serve as the primary imaging modality and AI algorithms generate the corresponding CT overlays to provide both soft tissue and bony detail from a single acquisition. Additional software capable of automated data subtraction and image overlap may further assist the radiologist and treating clinician in determining the contributing factors to neuroforaminal stenosis, offering a more integrated and precise evaluation of disease pathology (Maspero et al., 2020; Lerner et al., 2022).

Despite this promise, several barriers remain. AI models require large, high-quality and representative training datasets to achieve generalisable performance. There are few publicly available datasets for cervical spine imaging. They also currently rely on algorithms derived from a base truth or standard formulated by human assessment which could limit their accuracy. There are also challenges in ensuring transparency, explainability and regulatory compliance for AI-driven clinical decision tools. Furthermore, the risk of over-reliance on algorithm outputs without adequate clinical oversight must be addressed through careful review and retention of raw imaging for verification (Ross and Spates, 2020).

6.4 Emerging research correlating with patient symptoms following the systematic review

Understanding how the radiological severity of cervical neuroforaminal stenosis correlates with patient symptoms is key to bridging the gap between anatomical diagnosis and surgical outcomes. Since the systematic review published in this thesis, several new studies have contributed to this field, spanning surgical cohorts, dynamic imaging innovations and quantitative assessment. These studies highlight that while higher grades of stenosis often align with greater symptoms and generally post-operative improvement the full story is more nuanced. The relationship is influenced by methodological variation, patient-specific factors and the imaging modality used. These findings underscore the need for standardised radiological grading with clinical, functional and where feasible, dynamic assessments to improve both prognostic accuracy and treatment decision-making.

Lambrechts et al. (2023) explored how the severity of cervical neuroforaminal stenosis impacts clinical outcomes. This involved patients who underwent ACDF for cervical radiculopathy and used the modified Kim grading system. They found that patients with severe stenosis experienced greater improvements in physical function post-operatively compared to those with moderate stenosis. This was despite similar motor recovery, suggesting a significant role for ACDF in relieving symptoms of severe compression.

Lee et al. (2024) examined the accuracy of radiology reports against the Kim grading system and clinical outcomes for 283 patients. They found that standard reporting often underestimated stenosis severity. Both moderate and severe stenosis correlated with motor weakness, underscoring the importance of aligning imaging grading with clinical assessment.

Hutchins et al. (2023) introduced an MRI-compatible compression device to simulate the Spurling test during scanning. In patients with intermittent radiculopathy, dynamic compression often increased stenosis grade and reproduced symptoms. Dynamic imaging can reveal mechanical causes of radiculopathy by showing increased stenosis during movement and reproducing symptoms.

Caffard et al. (2024) combined the Kim grading system with MRI-based quantification of fat infiltration in cervical paraspinal muscles. Severe stenosis was associated with greater muscle fat infiltration and poorer post-surgical functional outcomes. This highlights muscle quality as a potential biomarker.

Marco et al. (2023) compared patient pain drawings to MRI findings. The level of agreement was only moderate, indicating that pain mapping is clinically useful but should be interpreted with imaging for accurate localisation of radiculopathy.

Feuerriegel et al. (2024) used 7T MRI and the Park grading to assess nerve root compression. They found higher diagnostic confidence and better anatomical visibility than 3T MRI, which improved prediction of sensory and motor dysfunction and may help in pre-surgical planning.

Jia et al. (2022) established a minimum oblique sagittal foraminal area of 25.95 mm^2, values below that predicted worse surgical outcomes. Similarly, Ozaki et al. (2020) used angled CT slices to define a 2.7 mm bony stenosis cut-off which strongly linked with radiculopathy symptoms.

Yeni et al. (2020) examined post-operative foraminal motion using dynamic biplane X-ray and 3D CT tracking. They found reduced dynamic foraminal width, especially at C6/C7, was linked to worse long-term patient-reported outcomes, emphasising the importance of motion preservation.

Despite their contributions, these studies have several important limitations. Many were retrospective (Jia et al., 2022; Lambrechts et al., 2023; Lee et al., 2024), limiting causal inference and control of confounding factors. Single-centre designs and selective patient cohorts reduce generalisability, while small sample sizes in prospective work (Hutchins et al., 2023; Feuerriegel et al., 2024) can diminish the ability to detect effects. Technological constraints can also limit applicability, for example, ultra-high-field MRI (Feuerriegel et al., 2024) and dynamic MRI devices (Hutchins et al., 2023) are not widely available. They would be difficult to utilise in routine clinical practice at most surgical centres. Outcome measurement variability, including subjective patient reported outcome measures (Caffard et al., 2024) and pain drawings (Marco et al., 2023) further affect reliability. Finally, follow-up durations were often short or absent, limiting understanding of long-term relationships.

6.4.1 Does the measured severity correlate with symptom severity?

The published clinical correlation study (Meacock et al., 2024) aimed to correlate radiological measures of cervical neuroforaminal stenosis with NDI. This included the widely recognised Kim, mKim and Siller grading systems, with patient-reported outcomes before and after surgery. Despite surgical interventions improving overall patient outcomes, none of the radiological measures or grading systems effectively predicted the severity of pre-operative symptoms or the degree of post-operative improvement. The lack of correlation that I found suggests that current standard axial MRI and current grading systems may be inadequate for accurately assessing the precise nature of nerve root compression or guiding surgical decisions effectively.

Several methodological factors may also have weakened the ability of this study to detect true imaging-clinical associations. The variation in timing between MRI acquisition and pre-operative NDI assessment is one such limitation. MRI scans were accepted if performed within one year of surgery, therefore, the scan may not have reflected the anatomical or biological state present when baseline disability was recorded. This temporal mismatch may have weakened any true association between radiological features and clinical function, biasing correlations towards the null.

Several parametric comparisons were also affected by unbalanced or very small subgroup sizes. Although NDI was approximately normally distributed overall, this may not have held within sparse subgroups, reducing the reliability of p values and contributing to type II error, particularly where one group contained only a few observations. A further limitation is that the analysis of the relationship between pre-operative NDI and change in NDI may overstate the strength of this association, because change scores are mathematically coupled to their baseline values. Patients with higher baseline NDI have greater scope for numerical improvement, which can inflate correlation estimates and may also reflect regression to the mean rather than a true prognostic effect. The finding that greater baseline disability was associated with greater reduction in NDI should therefore be interpreted cautiously.

Recent research in this thesis shows that while cervical foraminal stenosis severity measured on imaging often grossly correlates with clinical symptoms and functional outcomes, the relationship remains complex. Factors such as dynamic compression and imaging plane optimisation significantly influence diagnostic precision. Variability in study design, sample size, grading systems and follow-up duration further limits the generalisability of findings. These limitations highlight the importance of future research that incorporates standardised grading, multicentre recruitment and longitudinal outcome tracking. There would ideally be integrated static and dynamic imaging with objective functional metrics. Such an approach may be able to refine prognostic modelling and ensure that radiological assessments translate more reliably into meaningful clinical decision-making.

6.4.2 Why do some people have symptoms and others don't with the same degree of stenosis?

Radiological appearance of cervical foraminal stenosis does not always correlate with the presence or severity of symptoms. This is consistently reported in the literature and reflected in the findings of this thesis. This mismatch is multifactorial and will be discussed further in this section. It arises from several factors including anatomical variability, dynamic changes, inflammatory mechanisms, individual pain perception, coexisting pathology, limitations in imaging methodology and temporal fluctuation.

Anatomical variation in foraminal size and nerve root diameter means that patients with identical degrees of bony or disc encroachment may have widely differing clinical consequences. Patients with naturally wider foramina may tolerate substantial narrowing without neural compromise, whereas those with smaller foramina may become symptomatic with only minor reduction in space. The static nature of routine MRI and CT further contributes to this mismatch. Standard imaging is typically acquired with the neck in a neutral position, yet the neuroforamina size can change with movement, particularly extension, which often reduces the CSA. Such "dynamic stenosis" may be clinically significant but underestimated on neutral-position imaging (Mao, Sean J Driscoll, et al., 2016).

Symptoms are not determined solely by mechanical factors. Inflammatory and biochemical changes within the neuroforamina can play a significant role. Local oedema, granulation tissue or acute disc herniation, may provoke symptoms in one patient but another with similar static narrowing with no inflammatory component may remain asymptomatic. Chronic low-grade compression can lead to neural adaptation, whereas acute compression tends to produce pain (Byun et al., 2012; Cunha et al., 2018).

Individual differences in pain perception and central modulation add further complexity. It is commonly recognised that “pain is what the patient says it is” highlighting the individualistic nature of the sensation (McCaffery, 1968). Genetic variability in nociceptive pathways, psychosocial resilience, prior pain experiences and central sensitisation can influence whether neural compromise leads to clinical symptoms. Coexisting pathology, such as cervical myelopathy, peripheral neuropathy or shoulder disease, may mask or mimic radiculopathy, altering the clinical presentation and potentially delaying diagnosis (Woolf, 2011; Bjorland et al., 2016).

Imaging methodology also plays a role. Grading systems, including those evaluated in this thesis, categorise stenosis into discrete severity levels rather than the continuous compression present. These categories fail to capture subtle but clinically relevant variations in nerve root contact or deformation. Technical factors such as image plane orientation, slice thickness and resolution can lead to apparently equivalent grades representing slightly different anatomical actualities (Seo and Lee, 2023). The inter-observer variability demonstrated in this thesis highlights that grading reproducibility does not always equate to identical pathology (Meacock et al., 2023; Meacock et al., 2024). Clinical radiological discordance in cervical neuroforaminal stenosis is the product of multiple interacting factors. This underscores the importance of interpreting radiological grading alongside detailed clinical assessment. When possible, include dynamic and quantitative imaging measures to improve the prediction of functional impairment and surgical outcomes. Finally, timing matters. Patients imaged during a symptomatic flare may show more pronounced compromise than when scanned during remission. Given that foraminal stenosis can have a fluctuating course, a single imaging time point may not reflect the peak disease state.

6.5 Does the anatomical appearance affect surgical outcome?

The clinical correlation study (Meacock et al., 2024) further examined whether specific surgical approaches (ACD or PCF), were associated with differential outcomes based on the morphology and severity of stenosis assessed radiologically. Interestingly, no significant differences were observed in patient outcomes between these surgical techniques, even when radiological features suggested specific types or locations of nerve root compression. This finding emphasises that current imaging practices and grading systems do not reliably inform optimal surgical strategy, highlighting the need for more sophisticated imaging modalities.

6.5.1 Anterior verses posterior cervical foraminal impingement

Cervical foraminal stenosis can be caused by a variety of structural changes and the primary vector of compression, whether anterior or posterior, may have distinct anatomical, clinical and surgical implications. Although most grading systems treat all foraminal narrowing as equivalent, separating anterior from posterior pathology could improve both prognostic accuracy and surgical planning.

Anterior stenosis most frequently arises from uncovertebral joint osteophytes, intervertebral disc bulges or herniations. It can be focal and often causes deformation of the ventral aspect of the nerve root during the disease process (Carette, 2005; Margetis et al., 2025). Posterior impingement is usually the result of facet joint hypertrophy or thickening of the ligamentum flavum. This produces a more broad-based dorsal narrowing that can involve both the dorsal root ganglion and the vascular supply to the nerve root. Pressure on the nerve can cause sensory deficits, motor weakness or radicular pain with the patient commonly presenting with a mixture of symptoms (Abbed and Coumans, 2007). Posterior narrowing is also more likely to be accentuated during neck extension due to facet joints moving towards each other, whereas certain anterior pathologies may demonstrate greater compression during flexion due to disc herniation (Sayit et al., 2013).

The vector of compression has important implications for surgical approach. Anterior compression is theorised to be best addressed with ACDF and posterior compression with PCF. However, there is limited evidence to suggest that decompression outcomes are optimised when the surgical approach is matched to the dominant compression vector. Patient specific factors and the presence of combined anterior–posterior pathology often dictate the final strategy (Thomson et al., 2024; Meacock et al., 2024).

From a research perspective, the tendency for grading systems to ignore the anterior posterior distinction represents a potential source of clinical radiological mismatch. Two patients with the same overall foraminal diameter reduction may have different symptom profiles and surgical outcomes depending on whether the compression is primarily anterior or posterior. The quantitative methods proposed in this thesis particularly the documentation of the site and vector of maximal compression attempted to offer a way to capture this nuance in both clinical practice and future studies.

7 Conclusion

This thesis demonstrates that although radiological assessment plays a role in diagnosing and managing cervical neuroforaminal stenosis, current methodologies possess significant limitations. Grading classification techniques such as the Kim, modified Kim and Park systems show inconsistencies between different clinicians and do not accurately predict symptoms or surgical outcome. The natural anatomical variability seen at different cervical levels further complicates consistent grading. Importantly, standard axial MRI scans alone appear insufficient to fully characterise nerve root compression or guide surgical treatment decisions.

7.1 What should be measured in cervical foraminal stenosis?

7.1.1 Limitations of current measurement approaches

Conventional grading systems for cervical foraminal stenosis, such as the Kim and modified Kim systems, rely on categorical classifications derived from single axial MRI slices. While these systems are simple and reproducible, they inevitably discard much of the available anatomical information. They do not account for the true oblique course of the neuroforamen, the length of the stenotic segment or changes in dimension with posture or loading. In addition, they rarely consider the biological status of the nerve root itself. Small differences in image plane selection can also lead to substantial inter-observer variability which is present even when controlling for this by using the same image slice and broad grading categories may be too coarse to allow robust prognostic modelling.

7.1.2 True-axis anatomical measurements

Future assessment could prioritise continuous, anatomically accurate measurements. These measurements should be obtained along the true axis of the neuroforamen. Key parameters could include the minimum foraminal CSA and the minimum foraminal diameter, expressed both as absolute values and as a percentage relative to the patient's own uncompressed nerve root diameter (similar to that used within the Kim system). The length of the stenotic segment could also be recorded, alongside the site and vector of maximal compression (e.g. anterior due to uncovertebral osteophyte, posterior due to facet hypertrophy, proximal versus distal foramen).

7.1.3 Dynamic behaviour of the foramen

Static imaging in the neutral position fails to capture positional changes in the neuroforaminal calibre. Measuring the change in CSA or diameter between neutral and extension (or between unloaded and axial-loaded positions) could reveal clinically relevant “dynamic stenosis”. These changes should be expressed both in absolute terms and as a percentage change, with particular attention to side-to-side asymmetry and concordance with the symptomatic side.

7.1.4 Nerve-centred imaging biomarkers

Assessments should also consider the nerve root itself, rather than focusing solely on surrounding bony and soft tissue structures. The MRI signal ratio between the affected root and the corresponding reference root could reflect oedema or inflammation. Where available, DTI offers quantitative metrics which could be sampled at pre-foraminal, intra-foraminal and post-foraminal segments. Asymmetry indices between the symptomatic and contralateral sides may provide further insight into neural compromise.

7.1.5 Bony drivers of stenosis

Quantifying the bony components of stenosis is valuable for surgical planning. Measurements should include facet joint and uncovertebral osteophyte depth at the point of maximum narrowing. It could also include the osseous share of the stenosis, distinguishing between bony and soft tissue contributors. On CT the Hounsfield unit of osteophytes may serve as a proxy for bone density and hardness, which can influence the choice of decompression technique (Pirayesh Islamian et al., 2016).

7.1.6 Clinical linkage and prognostic variables

To improve clinical relevance, imaging measurements should be explicitly linked to patient presentation. Dermatomal concordance between imaging level and symptoms should be recorded, along with baseline functional scores such as the NDI and arm pain VAS. These should be reassessed post-operatively, with predefined minimal clinically important difference thresholds to facilitate outcome prediction.

7.1.7 Standardisation for reliability

Reliable assessment requires high-quality, standardised imaging. Three-dimensional isotropic T2-weighted sequences could be acquired to allow oblique multiplanar reconstructions, with slice thickness less than one millimetre for three-dimensional acquisitions. A written ROI protocol should be followed to standardise measurement boundaries, nerve root reference points and definitions for the start and end of the stenotic segment. Both sides should be measured and side-to-side ratios calculated to normalise values against the patient’s own anatomy.

7.1.8 Measuring the right thing

Accurate evaluation of cervical neuroforaminal stenosis likely requires moving beyond categorical grading of static axial images. The focus should shift towards quantifying the minimum CSA and diameter relative to nerve root size, stenotic length and compression vector with the functional dynamic changes, alongside nerve centred biomarkers. These parameters combined with clinical data could form a minimal core dataset for research and clinical practice, improving both the objectivity of assessment and the possibility of predicting surgical outcomes.

7.2 Future work

7.2.1 Advances in grading consistency

Future research should aim to include larger, more diverse populations to enhance the generalisability of findings. Studies, like those by Barnaure et al. (2022) and Costello et al. (2023) involved relatively small or single-institution samples. Expanding studies to include more varied demographic and clinical settings could ensure that findings apply to broader populations. Multicentre studies involving a variety of imaging technologies (like 1.5T and 3T) could provide richer data, bringing out the variations in patient anatomy and demographics. This approach would not only support broader applicability but also allow for stratified analyses. It could explore specific trends in age, race and sex similar to the morphometric research on 1000 patients performed by Razzouk et al. (2024) on cervical neuroforaminal dimensions.

Several studies used static imaging techniques. This limits insights into the dynamic behaviour of spinal structures. Mizouchi et al. (2020) used flexion–extension CT to show that spinal movement alters foraminal dimensions. Dynamic imaging could therefore reveal posture-dependent or intermittent neuroforaminal narrowing that static scans miss. Expanding research to include dynamic imaging could yield valuable clinical insights.

The grading system applied by Seo et al. (2023) relies heavily on qualitative assessments. While this system standardises grading and communication, it remains subjective. Developing quantitative metrics, potentially using AI and machine learning, could make grading more objective and consistent. AI algorithms trained on large datasets could help automate the identification and grading of stenosis severity. It could learn from image patterns to detect early signs of stenosis and assess change over time. AI may also incorporate patient specific anatomy which might influence the likelihood or impact of stenosis. Automating these processes would improve efficiency, especially in high-throughput clinical environments and support more precise, reproducible assessments (Laulloo et al., 2023).

Coudert et al. (2022) primarily focused on bony structures in their analyses, which limits insights into soft tissues. This is a fundamental component that plays a critical role in neuroforaminal stenosis. Future research could incorporate multimodal imaging, combining MRI with CT to separate soft-tissue from bony impingement. Combining modalities would give clinicians a holistic view of the cervical spine's anatomy and pathology. This would aid in the differentiation between soft tissue and bony impingement sources.

Wahezi et al. (2022) showed that orienting image planes to patient anatomy improves neuroforaminal assessment. Future studies could develop adaptive protocols that use a brief pre-scan evaluation to set scan angle and slice orientation. This approach would ensure that each scan provides optimised views of the foramina and surrounding structures. This improved view then allows for better diagnostic accuracy for patients with unusual anatomy or pathology.

Research like that performed by Razzouk et al. (2024) on normative cervical neuroforaminal dimensions provided valuable baseline data for assessing deviations associated with stenosis. Future studies should expand normative datasets to include wider age ranges, larger cohorts and diverse demographics providing benchmarks that are more representative of the general population. Such data would aid clinicians in distinguishing between normal anatomical variation and pathological changes. The goal is to reduce misdiagnosis and over-treatment. Once in clinical practice it may lead to the development of personalised diagnostic criteria, helping clinicians account for individual anatomical differences in stenosis assessments.

Most current research has focused on diagnosing established stenosis rather than monitoring its progression over time. Future studies should follow patients over time to detect early signs of neuroforaminal stenosis and map anatomical changes. Long-term data can help clinicians identify and monitor patients at high risk of symptomatic stenosis. This could support preventative care strategies, such as tailored physiotherapy or lifestyle modifications, potentially delaying or preventing the need for invasive future treatments.

While imaging advancements offer detailed anatomical insights, we need to link imaging assessments to patient outcomes. Future studies should investigate how imaging-based assessments of stenosis relate to functional status, pain and quality of life. For example, assessing how various grading systems, align with patient reported symptoms and post-treatment recovery would validate the clinical relevance of these grading systems. Such outcome-focused research could guide refinements in both diagnostic and therapeutic approaches, ensuring that imaging criteria reflect real-world patient experiences.

By addressing these future directions, researchers can build on the foundational studies in cervical neuroforaminal stenosis. This would enhance diagnostic accuracy, personalisation and outcome-based care. Having a holistic approach would better align imaging practices with patient needs, supporting more precise, tailored and effective management strategies for individuals affected by neuroforaminal stenosis.

7.2.2 Advances in symptom correlation

These studies highlight challenges commonly faced in clinical outcome research. Retrospective studies, limited sample sizes, poor generalisability and subjective outcome measures can reduce clinical utility. While these studies provide valuable insights into cervical radiculopathy and surgical outcomes, further research should use multicentre cohorts and extended follow-up periods. Long term follow-up ideally spanning ten years or more post-treatment would help to capture the full trajectory of patient recovery and any late complications. Such research could identify predictors of sustained benefit or recurrence, enabling clinicians to tailor interventions based on individual risk factors.

Improving diagnostic accuracy through advancements in MRI interpretation could also enhance clinical outcome research. Inconsistent or subjective interpretations of MRI findings can reduce the diagnostic value. Future studies could explore the use of AI-driven algorithms for grading, reducing variability in image interpretation and improving consistency in diagnosing cervical radiculopathy severity. Our team showed that AI grading can reduce interpretation variability (Laulloo et al., 2023). AI could analyse MRI scans to identify patterns linked to treatment outcomes, offering a more reliable approach than subjective radiological grading. Combining with advanced imaging, such as high Tesla MRI (Feuerriegel et al., 2024) or dynamic imaging during simulated compression (Hutchins et al., 2023) AI could yield more accurate depictions of nerve root compression aligning imaging findings more closely with clinical symptoms.

Future research on clinical outcomes in cervical spine interventions should focus on large-scale multicentre trials with pre-defined sample targets, include validated outcome measures (such as NDI and VAS), long-term follow-up and standardised advanced imaging protocols. By addressing these areas, future studies can provide more robust, actionable insights, ultimately improving treatment strategies and patient care in managing cervical radiculopathy.

7.2.3 Diffusion tensor imaging

DTI may have the potential to improve diagnostic precision in patients with conflicting clinical and radiological findings. It could be used to guide selection for surgical intervention and monitor microstructural recovery following decompression. In the context of cervical radiculopathy, such measures could complement standard axial and sagittal MRI by offering a more quantitative assessment of nerve integrity. The findings from my pilot study in chapter five provide early support for this by demonstrating that quantitative assessment of the cervical nerve roots using DTI is both technically feasible and capable of generating diffusion metrics. Although no statistically significant correlations were identified, trends were observed between these parameters and clinical outcomes. Higher QA values which reflect greater preservation of microstructural organisation were associated with lower pre-operative disability and smaller post-operative change in NDI. Lower QA values tended to correspond with greater pre-operative impairment and more marked post-operative improvement. Moderate negative correlations were also observed for ISO and RDI, suggesting that these measures may capture overlapping, less specific changes.

A further important next step for this work would be to expand DTI assessment beyond single-metric exploratory analysis towards a multi-parametric predictive model. Rather than considering FA, MD, QA, RDI and ISO in isolation, future studies could investigate whether combinations of diffusion metrics better predict symptom severity, baseline disability and post-operative recovery than any individual parameter alone. These models could also be correlated with established anatomical grading systems, including the Kim and mKim methods, to determine whether DTI provides complementary information to conventional morphological assessment or whether certain diffusion patterns align with increasing radiological stenosis severity. Repeat DTI measurements would also be valuable, both to assess test–retest reliability and to explore temporal changes in nerve microstructure before and after surgery or during conservative management. Finally, correlation with nerve conduction studies could help determine whether DTI abnormalities reflect physiologically meaningful nerve dysfunction, thereby strengthening its potential role as an imaging biomarker that links radiological appearance, neural integrity and clinical outcome.

These preliminary findings highlight the potential for DTI as a possible biomarker of neural compromise and functional outcome, offering complementary information to conventional MRI. Additionally, the absence of significant differences between symptomatic and asymptomatic sides may indicate either bilateral or diffuse microstructural changes or may simply reflect the small sample size and technical variability inherent in early studies. The ability to successfully extract multiple diffusion metrics from small anatomical structures shows DTI can be incorporated into cervical imaging workflows with consistent acquisition and operator technique. As imaging hardware, acquisition techniques and post-processing methodologies continue to evolve, DTI may emerge as a valuable aide to standard cervical spine MRI. It has the potential to enhance diagnostic confidence, refine prognostic assessment and enable more personalised management strategies in cervical radiculopathy.

7.3 Final statements

There is a need for advancements in imaging techniques and the establishment of standardised, objective radiological assessment criteria. Advanced imaging technologies, such as three-dimensional MRI and DTI, represent promising opportunities for future research and clinical application. These technologies may offer improved anatomical detail and accuracy in identifying nerve-root compression while better predicting clinical outcomes. In parallel, AI approaches may provide additional opportunities, for example through automated overlay of CT and MRI datasets to help determine whether bone or soft tissue is the main instigator of radiculopathy. With access to well-curated imaging and clinical datasets, AI could also be trained and validated for outcome prediction, potentially bridging the current gap between radiological appearances and patient prognosis. The careful integration and adoption of these advanced methodologies could improve diagnostic precision, support better-informed surgical decision-making and enhance overall future patient care.

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