Web Training Modules
Module 16: Cervical Spine Imaging
Anatomy ........................................................................................................................................................ 5

Upper Cervical Spine ........................................................................................................................................ 5
Atlas .......................................................................................................................................................... 5
Axis ......................................................................................................................................................... 6
Articulations ............................................................................................................................................ 6
Ligaments ............................................................................................................................................... 7
Vasculature ........................................................................................................................................... 7
Nerves ................................................................................................................................................... 7

Lower Cervical Spine ........................................................................................................................................ 8
C3-C7 ..................................................................................................................................................... 8
Intervertebral Discs ....................................................................................................................................... 9
Joints ..................................................................................................................................................... 9
Ligaments ............................................................................................................................................ 10
Vasculature ......................................................................................................................................... 11
Nerves ................................................................................................................................................. 12
Brachial Plexus ........................................................................................................................................ 14

Cervical Spinal Cord ...................................................................................................................................... 15

Pathology .......................................................................................................................................................... 16
Cervical Spinal Canal and Spinal Cord ........................................................................................................ 16
Spinal Canal Stenosis .................................................................................................................................... 16
Spinal Cord Injuries ................................................................................................................................... 17
Cervical Spondylotic Myelopathy ............................................................................................................... 18
Degeneration of Cervical Spine and Discs ................................................................................................. 21
Osteoarthritis .......................................................................................................................................... 21
Osteophytes ............................................................................................................................................ 22
Disc Degeneration ....................................................................................................................................... 22
Acute Cervical Injuries ................................................................................................................................ 23
Hyperflexion Injuries .................................................................................................................................. 23
Hyperextension Injuries ............................................................................................................................. 28
Fractures Due to Axial Loading .................................................................................................................. 31
Additional Injuries ....................................................................................................................................... 32
Tumors and Diseases of the Cervical Spine ................................................................. 34

Metastasis .................................................................................................................. 35

Primary Benign Extradural Tumors ........................................................................ 36

Osteochondroma ..................................................................................................... 36

Primary Malignant Extradural Tumors .................................................................. 37

Multiple Myeloma .................................................................................................. 37

Chordomas ............................................................................................................. 39

Intradural-Extramedullary Tumors ......................................................................... 41

Spinal Schwannomas ............................................................................................. 41

Spinal Meningiomas ............................................................................................... 42

Ependymomas ......................................................................................................... 42

Intradural-Intramedullary Tumors .......................................................................... 44

Gangliogliomas ........................................................................................................ 44

Hemangioblastomas ............................................................................................... 45

Astrocytomas .......................................................................................................... 47

Oligodendrogliomas ............................................................................................... 48

Teratomas ............................................................................................................... 49

PNET (Primitive Neuroectodermal Tumor) ............................................................ 51

Forestier Disease .................................................................................................. 53

MRI Coils for Cervical Spine Imaging ................................................................. 54

Oasis Open MRI System ....................................................................................... 54

Coils and Positioning ............................................................................................. 55

RAPID Cervical Coil .............................................................................................. 56

CTL Spine Coil ....................................................................................................... 57

Solenoid Coil ........................................................................................................... 58

Echelon OVAL MRI System .................................................................................... 59

Coils and Positioning ............................................................................................. 59

WIT Posterior Head/Neck Coil with WIT Anterior Neck Coil Attachment .......... 60

WIT Posterior Head/Neck Coil with WIT Anterior NeuroVascular Attachment ... 61

Echelon MRI System .............................................................................................. 62

Coils and Positioning ............................................................................................. 62
Anatomy

The cervical spine is the most superior portion of the vertebral column, consisting of the first 7 vertebrae of the spine. It performs several crucial roles, including:

- **Housing and protecting the spinal cord** – Spinal cord relays messages from the brain to the rest of the body; the cord runs through the cervical and thoracic spine, ending at the superior aspect of the lumbar spine
- **Supporting the head and its movement** – Cervical spine supports the head, which weighs between 10 and 13 pounds; it allows for head’s flexibility, including rotational, forward/back, and side bending motions, while connecting it to the relatively immobile thoracic spine
- **Facilitating flow of blood to the brain** – Vertebral foramina in the cervical spine provide a passageway for vertebral arteries to pass and ensure proper blood flow to the brain; these foramina are only present in the vertebrae of the cervical spine

Upper Cervical Spine

Atlas

The upper cervical spine is made up of the atlas (C1) and axis (C2), which are quite different from the rest of the cervical spine. The atlas is ring-shaped and does not have a vertebral body or spinous process. There are no weight-bearing discs between the occiput and C1, or between C1 and C2. Head weight is transferred to C3 by the large articular processes and facets of C1 and C2. The atlas consists of a thick anterior arch (with an articular facet for the dens of the axis), a thin posterior arch (with a groove for the vertebral artery and C1 spinal nerve), 2 prominent lateral masses, and 2 transverse processes (Figure 1). The transverse processes enclose the transverse foramina, through which the vertebral arteries pass. On each lateral mass is a superior and inferior facet joint. The superior facets articulate with the occipital condyles, while the inferior facets articulate with the superior facets of the axis. The lateral masses also provide an attachment site for the transverse ligament of the atlas.
Axis

Fused remnants of the body of the atlas have become part of the axis (C2), where they are called the odontoid process, or dens, which extends superiorly from the anterior portion of the vertebra. The odontoid process articulates with the anterior arch of the atlas via its anterior articular facet, and is held in place by the transverse ligament. The axis is composed of a vertebral body, heavy pedicles, laminae, and transverse processes, which serve as attachment points for muscles. The axis articulates with the atlas via its superior articular facets (Figure 1).

Articulations

The atlas articulates superiorly with the occiput of the cranium, creating the atlanto-occipital joints, which are responsible for 50% of flexion and extension. These articulations occur between the superior facets of the lateral masses of the atlas and the occipital condyles at the base of the cranium. These are condyloid type synovial joints that permit flexion of the head. The atlas articulates inferiorly with the axis, creating the atlanto-axial joints, which are responsible for 50% of all cervical rotation. There are 2 lateral atlanto-axial joints, formed by the articulation between the inferior facets of the lateral masses of C1 and the superior facets of C2. These lateral atlanto-axial joints are plane type synovial joints. The medial atlanto-axial joint is formed by the articulation of the dens of C2 with the articular facet of C1, creating a pivot type synovial joint. This allows for rotation of the head independently of the torso.
Ligaments

The external and internal ligaments secure the craniocervical junction and the atlantoaxial joints of the upper cervical spine. The external ligaments include the atlanto-occipital, anterior atlanto-occipital, and anterior longitudinal ligaments. The internal ligaments have 5 components, which include:

- **Transverse ligament** – connects the lateral masses of the atlas, and in so doing, holds the odontoid process in place against the posterior aspect of the anterior arch of the atlas, preventing anterior subluxation of C1 on C2; allows rotation of the atlas on the dens, and is responsible for stabilizing the cervical spine during flexion, extension, and lateral bending
- **Accessory ligaments** – arise posterior to and in conjunction with the transverse ligament, and insert into the lateral aspect of the atlanto-axial joint; the apical ligament lies anterior to the lip of the foramen magnum and inserts into the apex of the odontoid process
- **Alar ligaments** – paired ligaments that secure the apex of the odontoid to the anterior foramen magnum; prevent excessive lateral and rotational motion while allowing flexion and extension; if damaged, as in whiplash injury, joint complex becomes hypermobile, which can lead to kinking of vertebral arteries, and stimulation of nociceptors and mechanoreceptors; this may be associated with the typical complaints of headache, neck pain, and dizziness experienced by those with whiplash injuries
- **Tectorial membrane** – a continuation of the posterior longitudinal ligament to the anterior margin of the foramen magnum
- **Accessory atlanto-axial ligament** – connects the atlas to the axis, and continues cephalad to the occipital bone; becomes maximally taut with 5-8° of head rotation or 5-10° of cervical flexion, and is lax with cervical extension; participates in craniocervical stability

Vasculature

In the atlas, the vertebral artery runs along the groove for the vertebral artery, rather than passing through the transverse foramen, as it does in most other cervical vertebrae. There is an extensive arterial anastomotic network around the odontoid, fed by the paired anterior and posterior ascending arteries arising from the vertebral arteries around the C3 level, and the carotid arterial arcade from the base of the skull. The anterior and posterior ascending arteries reach the base of the odontoid via the accessory ligaments, and run cephalad at the periphery to reach the tip of the process. The anastomotic arcade also receives tributaries from the ascending pharyngeal arteries that join the arcade after passing through the occipital condyle.

Nerves

The atlanto-occipital and atlantoaxial facet joints are innervated by the anterior rami of the first and second cervical spinal nerves. Numbering of the spinal nerves commences above the atlas, leading to a total of 8 cervical spinal nerves. The first cervical spinal nerve exits between the occiput and the atlas, or C1 vertebra.
Lower Cervical Spine

C3-C7

The 5 cervical vertebrae that make up the lower cervical spine, C3-C7, are similar to each other, but quite different from C1 and C2, as well as distinguishable from thoracic vertebrae. They have triangular vertebral foramina, bifid spinous processes (split in two distally), and transverse foramina, which are holes in the transverse processes that give passage to the vertebral artery, vein, and sympathetic nerves (Figure 2). The C3-C7 vertebrae each have a vertebral body that is concave on its superior surface, and convex on its inferior surface. The superior lateral margins of the vertebral bodies have raised processes or hooks called uncinate processes, each of which articulates with a depressed area on the inferior lateral aspect of the superior vertebral body, called the echancrure or anvil. These articulations are called uncovertebral joints, or the joints of Luschka, although they are fibrous joints rather than true joints. They can develop osteophytic spurs, which can narrow the intervertebral foramina. A bony vertebral arch wraps around the spinal cord toward the back and consists of two pedicles and two laminae. The pedicles connect with the vertebral body in the front, and the laminae transition into the spinous process in the back of the vertebra. The spinous processes of C3-C6 are usually bifid, while the spinous process of C7 is nonbifid but prominent and easily palpated. C7, also called the vertebra prominens, connects with the top of the thoracic spine, T1, to form the cervicothoracic junction, or C7-T1. C7 is larger than the cervical vertebrae above it, and has a different shape, in order to better fit with T1 below it. Because of its larger size and key location at the cervicothoracic junction, several more muscles connect to C7’s spinous process compared to other cervical vertebrae.

Figure 2 Axial MR image of lower cervical spine
Intervertebral Discs

Intervertebral discs are located between the vertebral bodies of C2-C7. They are composed of 4 parts, including the nucleus pulposus in the middle, the annulus fibrosis surrounding the nucleus, and 2 end plates that are attached to the adjacent vertebral bodies. The discs are thicker anteriorly, which contributes to normal cervical lordosis. They serve as force dissipators, transmitting compressive loads throughout a range of motion. In the cervical spine, the intervertebral discs are involved in motion, stability, and weight-bearing. The nucleus pulposus is a loose fibrous network suspended in mucoprotein gel that is sealed by the annulus fibrosis. The annular fibers of the disc are composed of collagenous sheets (lamellae) that are oriented at a 65-70° angle from the vertical, and alternate in direction with each successive sheet. As a result, they are vulnerable to injury by rotation forces, as only half of the lamellae are oriented to withstand force applied in this direction. The middle and outer one third of the annulus is innervated by nociceptors which are sensory neurons that respond to potentially damaging stimuli by sending signals to the spinal cord and brain causing the perception of pain. Phospholipase A2 has been found in the disc, and may be an inflammatory mediator. Intervertebral discs need to be well-hydrated in order to maintain their strength and softness to serve as the body’s major carrier of axial load. With age, the cervical discs lose water, stiffen, and become less flexible in adjusting to compression. These degenerative changes may result in a herniated cervical disc, which occurs when the disc’s inner core extrudes through its outer core and comes in contact with the spinal nerve root. In other instances, the cervical disc may degenerate as a result of direct trauma or gradual changes. With no blood supply, and very few nerve endings, a cervical disc cannot repair itself.

Joints

There are two different joints present in the lower cervical spine that are found throughout the remaining vertebral column. Adjacent vertebral bodies are joined by intervertebral discs, made of fibrocartilage. This is a type of cartilaginous joint, known as a symphysis. Most vertebrae also have a pair of facet joints located between the pedicle and lamina on each side of the vertebral arch, formed by the articulation of superior and inferior articular processes from adjacent vertebrae. These are diarthrodial synovial type joints, also known as Zygapophysial joints, or Z joints, with fibrous capsules lined with smooth cartilage. The joint capsules are more lax in the lower cervical spine than in other areas of the spine to allow gliding movements of the facets, with the joint capsules being weakest posteriorly. The small ranges of motion between any two vertebrae can add up to significant ranges of motion for the entire cervical spine in terms of rotation, forward/backward, and side bending. The facet joints are inclined at an angle of 45° from the horizontal plane and 85° from the sagittal plane. This alignment helps prevent excessive anterior translation, and is important in weight-bearing.
Ligaments

Most of the ligaments associated with the lower cervical spine are present throughout the vertebral column. The anterior and posterior longitudinal ligaments are long ligaments that run from the axis to the sacrum, covering the vertebral bodies and intervertebral discs. They are the main stabilizers of the intervertebral joints. The ligamentum flavum connects the laminae of adjacent vertebrae, while the interspinous ligaments connect the spinous processes of adjacent vertebrae. Both also help control for excessive flexion and anterior translation. The cervical spine also contains the nuchal ligament, which is a continuation of the supraspinous ligament. It attaches to the tips of the spinous processes from C1-C7, and provides the proximal attachment for the rhomboids and trapezius, as well as having a prominent role in stabilizing the cervical spine.

Ligaments of the cervical spine can be interpreted as being set up in columns- anterior, middle, and posterior (Figure 3). The anterior column consists of the anterior longitudinal ligament and the anterior two thirds of the vertebral bodies, the annulus fibrosus, and the intervertebral discs. The middle column is composed of the posterior longitudinal ligament and the posterior one third of the vertebral bodies, the annulus fibrosus, and the intervertebral disks. The posterior column is made up of the posterior arches, including the pedicles, transverse processes, articulating facets, laminae, and spinous processes. The anterior and posterior longitudinal ligaments maintain the structural integrity of the anterior and middle columns, while the posterior column alignment is stabilized by a complex of ligaments, including the nuchal and capsular ligaments, and the ligamentum flavum. If one of the 3 columns is disrupted as a result of trauma, stability is provided by the other 2 columns, and cord injury is usually prevented. If 2 columns are disrupted, spinal cord injury is more likely, as the spine may then move as separate units.
Vasculature

The vascular anatomy of C3-C7 consists of a larger anterior spinal artery located in the central sulcus of the cord, and paired posterior spinal arteries located on the dorsum of the cord. It is believed that the anterior two thirds of the cord is supplied by the anterior spinal artery, and the posterior one third is supplied by the posterior arteries. The anterior spinal artery arises from the vertebral arteries. The posterior spinal artery arises from the vertebral artery in 25% of humans, and from the posterior inferior cerebellar artery in 75% of humans.

The right and left vertebral arteries arise from the subclavian arteries. They ascend up the posterior side of the neck, through the transverse foramina in the transverse processes of the cervical vertebrae. The vertebral arteries do not supply branches to the neck or extra-cranial structures.

Like the vertebral arteries, the carotid arteries do not give off any branches in the neck, but they are often the subject of MRI studies (Figure 4).

The right common carotid arises from a bifurcation of the brachiocephalic trunk, while the left common carotid branches directly from the aortic arch. The right and left common carotids ascend up the neck lateral to the trachea. At the level of the superior margin of the thyroid cartilage (approx. C4), the common carotids bifurcate into the external and internal carotid arteries. The external carotid arteries supply areas of the head and neck external to the cranium, while the internal carotids supply the brain, eyes, and forehead. This bifurcation occurs in an anatomical area known as the carotid triangle. Both the common and internal carotids are slightly dilated in this region, known as the carotid sinus, which is important in detecting and regulating blood pressure. The carotid sinus contains specific sensory cells, called baroreceptors, which detect “stretch” as a measure of blood pressure. The glossopharyngeal nerve feeds this information to the brain, where it is used to regulate blood pressure. In some people, the baroreceptors are hypersensitive to “stretch”, as a result of which external pressure on the carotid sinus can cause slowing of the heart rate and a decrease in blood pressure. The brain becomes under
perfused, resulting in syncope. For these patients, checking the pulse at the carotid triangle is not advised. The dilation at the carotid sinus also produces turbulent blood flow. This increases the risk of atheroma formation in this area, with the internal carotid more susceptible than the other vessels. Atheroma is the fatty material that forms plaques in the arteries and occurs in atherosclerosis, which is one of the three subtypes of arteriosclerosis. Atherosclerotic thickening of the inner layer of the artery wall reduces blood flow to the brain, resulting in a variety of neurological symptoms, including headache, dizziness, and muscular weakness. Complete occlusion of blood flow results in a stroke. External to the carotid sinus is a small cluster of peripheral chemoreceptors called the carotid body. These cells sense the oxygen and carbon dioxide levels in the blood, and relay this information to the brain to regulate the heart and breathing rate.

Arteries that supply the neck arise from the right and left subclavian arteries as the thyrocervical trunk. Numerous vessels supply the neck, including:

- **Inferior thyroid artery** – first branch of the thyrocervical trunk; supplies the thyroid gland
- **Ascending cervical artery** – arises from the inferior thyroid artery as it turns medially in the neck; supplies the posterior prevertebral muscles
- **Transverse cervical artery** – next lateral branch from the thyrocervical trunk; crosses the base of the carotid triangle, supplies the trapezius and rhomboid muscles
- **Suprascapular artery** – remaining lateral branch from the thyrocervical trunk; supplies the posterior shoulder area

**Nerves**

The spinal nerves are intimately related to the cervical vertebrae. They extend from above their respective vertebrae, through the intervertebral foramen created by the joints at the articular processes. The C7 vertebra is an exception, with a set of spinal nerves extending from above (C7) and below (C8) the vertebra. This results in 8 spinal nerves associated with 7 cervical vertebrae.

Spinal nerves are collections of axons of sensory and motor neurons, and are part of the peripheral nervous system. They are formed from nerve roots that arise directly from the spinal cord. Axons of sensory neurons make up the posterior root, and axons of motor neurons make up most of the anterior root (although reports state that some 30% of anterior root axons are sensory). Spinal nerves are very short. They form within the intervertebral foramina, and branch just beyond into anterior and posterior rami. The branches of these rami are distributed body-wide below the head, providing a vehicle for acquisition by the central nervous system of sensory information from internal and external receptors, and a means of disseminating motor commands to skeletal, smooth, and cardiac muscle, and to glands. The anterior rami of the cervical spinal nerves (and T1 spinal nerve) form interconnecting networks from which the nerves to the neck and the upper limb are derived. The source of a nerve to the limbs can be traced to the collection of spinal nerves that form it (e.g., C5-C8 spinal nerves).
The cervical nerves provide control and sensation to different parts of the body based on the spinal level from where they branch out, as noted below:

- **C1, C2, and C3** – Control the head and neck, including movements forward, backward, and to the sides; also play key roles in breathing
- **C4** – Helps control the shoulders as well as the diaphragm for breathing
- **C5** – Controls upper body muscles, such as the deltoids (rounded contours of the shoulders) and biceps (allow flexion of the elbow and rotation of the forearm)
- **C6** – Controls wrist extensors, provides some innervation to biceps
- **C7** – Controls triceps (elbow straightening)
- **C8** – Controls the hands

Spinal nerves and their roots have fairly tight quarters. The intervertebral foramina in which they form are largest at C2-C3, and progressively decrease in size down to C6-C7 (Figure 5). The spinal nerve and spinal ganglion occupy 25-33% of the foraminal space. Nerve roots are vulnerable to irritation (radiculitis) from encroaching, hypertrophic bone in the lateral recesses (degenerative joint disease), from bulging intervertebral discs (degenerative disc disease), or from cysts, meningeal tumors, etc. With compression of axons, or blood vessels supplying the axons, functional deficits can result (radiculopathy, sensory loss, motor loss, and/or tendon reflex change).

![Figure 5 Sagittal MR image showing nerve roots of cervical spine](image-url)
Brachial Plexus

The anterior rami of spinal nerves C5-T1 (plus or minus one level) form the brachial plexus, from which the major nerves to the structures of the upper limb arise. These rami form the roots of the plexus, while further branching and joining of fibers in the neck, supraclavicular area, and axilla result in the formation of the five major nerves of the upper limb (Figure 6). The musculocutaneous nerve (C5-C7) supplies the anterior arm muscles, and is cutaneous in the forearm. C5 and/or C6 nerve root compression can weaken these muscles. The median nerve (C5-C8, T1), also known as the carpenter’s nerve, supplies the anterior forearm muscles and the thenar muscles. A C6 nerve root compression can result in some degree of sensory deficit to fingers 1-3 and weakness in thumb movement, similar to carpal tunnel syndrome. The ulnar nerve (C8-T1), or musician’s nerve, supplies certain muscles of the forearm and most intrinsic muscles of the hand. It is subject to trauma as it rounds the elbow, possibly resulting in ulnar-side finger pain, hand weakness or abnormal little finger position. A C8 nerve compression can cause similar complaints. The axillary nerve (C5-C6) wraps around the neck of the humerus to supply the deltoid and teres minor muscles. The radial nerve (C5-C8, T1) supplies the triceps, brachioradialis, and posterior forearm (extensor) muscles, moving the wrist and hand. A C7 radiculopathy is characterized by a weak triceps and loss of the triceps jerk (deep tendon reflex).

Figure 6 Coronal MR image showing nerve roots of the brachial plexus
Cervical Spinal Cord

The spinal cord begins at the foramen magnum of the skull and ends at the L1 or L2 vertebral level. It is located within the vertebral foramina of the cervical, thoracic and lumbar vertebrae, surrounded and protected by the posterior aspect of the vertebral body, pedicles, articular processes, lamina and spinous processes.

The spinal cord consists of a central mass of gray matter arranged in the form of an “H”, with a peripheral array of white matter (funiculi) consisting of descending and ascending tracts. The amount of white matter decreases as the cord progresses distally. The gray posterior horns receive the central processes of sensory neurons, and direct incoming impulses to the adjacent white matter for conduction to other cord levels or higher centers. The anterior horns include lower motor neurons that represent the “final common pathway” for motor commands to muscle. Lateral horns do not exist in the cervical spinal cord, but are present in the thoracic and upper lumbar regions. Spinal reflexes occur in the gray matter in conjunction with facilitatory and inhibitory influences from higher centers.

The spinal cord bulges slightly in the lower cervical and lumbar regions in relation to the presence of large numbers of axons associated with the upper and lower limbs. In the cervical region, the lateral dimension of the spinal cord spans 13-14mm, with the anterior-posterior extent measuring 7 mm. An additional 1 mm is necessary for cerebrospinal fluid (CSF) anteriorly and posteriorly, as well as 1 mm for the dura, which is the tough, protective, fibrous outer covering of the spinal cord. A total of 11 mm is needed for the cervical spinal cord. Exiting at each vertebral level is the spinal nerve, which is the result of the union of the anterior and posterior nerve roots.
Pathology

The American College of Radiology recommends routine MRI as the most appropriate imaging study in patients with chronic neck pain who have neurologic signs or symptoms but normal radiographs. MRI has become the method of choice for imaging the neck to detect significant soft-tissue pathology, such as disc herniation, as it can detect ligament and disc disruption, which cannot be demonstrated by other imaging studies. MRI is quite useful in evaluating the amount of cerebrospinal fluid surrounding the cord in the evaluation of patients with cervical canal stenosis, and is considered the imaging method of choice for the evaluation of cervical radiculopathy.

Cervical Spinal Canal and Spinal Cord

Spinal Canal Stenosis

Causes of spinal stenosis, an abnormal narrowing of the spinal canal, may include:

- **Overgrowth of bone** – “Wear and tear” damage from osteoarthritis on the cervical spine bones can prompt the formation of bone spurs, which can grow into the spinal canal; Paget’s disease, a bone disease that usually affects adults, can cause bone overgrowth in the spine
- **Herniated discs** – Discs tend to dry out with age; cracks in a disc's exterior may allow some of the soft inner material to escape and press on the spinal cord or nerves
- **Thickened ligaments** – Ligaments may become stiff and thickened over time, and these thickened ligaments can bulge into the spinal canal
- **Tumors** – Abnormal growths can form inside the spinal cord, within the membranes that cover the spinal cord, or in the space between the spinal cord and vertebrae
- **Spinal Injuries** – Motor vehicle accidents and other major trauma can cause dislocations or fractures of one or more vertebrae; displaced bone from a spinal fracture may damage the contents of the spinal canal; swelling of adjacent tissue immediately following back surgery can also put pressure on the spinal cord or nerves
Spinal Cord Injuries

There are two types of injuries to the spinal cord:

- **Non-hemorrhagic** – only high signal on MR due to edema
- **Hemorrhagic** – areas of low signal intensity within the area of edema

There is a strong correlation between the length of the spinal cord edema, and the clinical outcome. However, the most important factor is whether or not there is hemorrhage, as hemorrhagic spinal cord injury has an extremely poor outcome (Figure 7).

![Figure 7 Non-hemorrhagic spinal cord injury on left (yellow arrow); hemorrhagic spinal cord injury on right (red arrows)](image)

Spinal cord injuries are typically classified by the spinal nerve root level at which function is lost or impaired. For example, a C6 spinal cord injury would result in loss of the C6 nerve root’s function, as well as all of the nerve roots below. The patient would be able to breathe and move their head and shoulders well, but would struggle with moving their arms, and would likely have no ability to move their trunk or legs. Sensations below the shoulders would also likely be impaired or lost. A spinal cord injury at any of the top three levels (C1, C2, or C3) is usually fatal, unless the ability to breathe is quickly restored by an emergency medical responder.
Spinal cord syndromes due to injury include:

- **Central cord syndrome** – Most common incomplete cord syndrome; frequently found in elderly with underlying spondylosis, or in younger people with severe extension injury; upper extremity deficit is greater than lower extremity deficit, as lower extremity corticospinal tracts are located laterally in the cord
- **Anterior cord syndrome** – Seen in flexion injuries, such as burst fracture, flexion tear drop fracture, and herniated disc; presents with immediate paralysis, as the corticospinal tracts are located in the anterior aspect of the spinal cord
- **Brown-Sequard syndrome** – Ipsilateral motor weakness and contralateral sensory deficit due to hemisection of spinal cord; may result from rotational injury, such as fracture-dislocation or from penetrating trauma, such as stab wound
- **Posterior cord syndrome** – Uncommon syndrome, due to extension injury; loss of positioning sense due to disruption of dorsal columns; good prognosis
- **Complete spinal cord injury** – Total absence of sensation and motor function caudal to the level of injury

## Cervical Spondylotic Myelopathy

This condition commonly occurs in patients over the age of 50, arising when the spinal cord becomes compressed due to degenerative changes that occur in the joints and ligaments of the spinal column. As the discs in the spine begin to age, they lose height and begin to bulge. They also lose water content, so they begin to dry out and become stiffer. This problem causes settling, or collapsing, of the disc spaces, and loss of disc space height. As the discs lose height, the vertebrae move closer together. The body responds to the collapsed disc by forming more bone, actually bone spurs or osteophytes, around the disc in order to strengthen it. The bone spurs contribute to the overall stiffening of the spine, and may also cause narrowing of the spinal canal, in which case the spinal cord is compressed. As the discs deteriorate with age, they become more prone to herniation, which often occurs with lifting, pulling, bending, or twisting movements. When a herniated disc bulges out toward the spinal canal, it can put pressure on the spinal cord or nerve roots. A sudden onset of cervical myelopathy can occur in cases of large, often spontaneous, intervertebral disc herniation onto the cord.

Myelopathy can arise from other conditions that cause spinal cord compression which may have similar symptoms, but are unrelated to disc degeneration. Rheumatoid arthritis is an autoimmune disease, meaning the immune system attacks its own tissues. In this case, immune cells attack the synovium, which is the thin membrane that lines the joints. As the synovium swells, it may lead to pain and stiffness and, in severe cases, destruction of the facet joints in the cervical spine. Degenerative changes are further complicated by the development of instability. Osteoarthritis in perishing joints can cause an inability to hold the vertebrae in alignment during movement and at rest. A forwards-and-backwards slippage takes place, which can change the space available to the cord quite rapidly and significantly during movements of the neck. Trauma to the neck, such as from a car accident, sports, or a fall, may also lead to myelopathy. Hyperextension or hyperflexion injuries from “rear end” vehicle collisions often affect the muscles and ligaments that support the vertebrae, and may lead to spinal cord compression. Additional causes of cervical spinal cord compression include tumor, abscess, hematomas, hernias, cysts, and congenital disorders.
It has been found that once the spinal canal has narrowed by 30%, symptoms of cervical myelopathy usually appear. The front-to-back reduction in the diameter of the spinal canal is usually the most damaging. Degenerative processes may continue until the spinal cord becomes deformed, in order to be accommodated in the new shape of the spinal canal. Once this causes deprivation of blood supply (ischemia), myelopathy develops. The pressure on the spinal cord becomes severe enough to compress the small blood vessels of the cord, so no oxygen reaches the nervous tissue, and the spinal cord becomes ischemic, impairing nerve function. The lack of oxygen (ischemia) is the root cause of the spinal cord damage, which is referred to as myelopathy. If the pressure is relieved quickly enough, there is no damage. Initially, the compression may be intermittent, and the cord can recover between cycles of compression. As the pressure becomes more intense and longer lasting, the insult caused by the repeated episodes of ischemia results in permanent tissue damage to the spinal cord. This damage may not recover well or, at times, not at all, even after surgical relief of the compression.

Myelopathy leads to impairment of function of the cervical spinal cord. The signs and symptoms of myelopathy are quite distinct from the neck pain of cervical osteoarthritis, which is movement dependent, and can radiate to the head and shoulders. Cervical myelopathy is the most common form of myelopathy, but it is often associated with relatively little or no pain. Direct pressure on the spinal cord may create a sensation of pins-and-needles (paresthesia) in the whole body. Initially, this may happen only on flexion of the neck, becoming more continuous as the condition worsens. Symptoms in the arms constitute a combination of cord failure at the affected level, and of compression and irritation of the cervical nerve roots which leave the neck at this site, termed radiculopathy. Clinical findings on examination will help to distinguish between what originates from the cord and what from the nerve roots. The definitive diagnosis is based on the characteristics and the distribution of the sensory and motor findings at examination.

Cervical myelopathy findings in the body below the neck depend on the configuration and severity of the ischemic lesion in the substance of the spinal cord. Usually there are varying measures of tightness of gait and numbness of the legs. These variations are an expression of the exact distribution of the myelopathy in the spinal cord of the individual patient. A transverse lesion of the spinal cord will affect all the modalities of cord transmission with spasticity of gait and increased tendon reflexes, with loss of appreciation of temperature, pain, and joint sense, and often with impairment of bladder and bowel control. More localized lesions may affect predominantly only one side of the cord. This will impair the motor function and joint sense on the side of the lesion, and the appreciation of temperature and pain on the side opposite to the lesion. A central lesion of the cord may present with predominantly hand symptoms.

Symptoms of cervical spondylotic myelopathy typically develop slowly and progress steadily over several years. These symptoms may include:

- Tingling or numbness in the arms, fingers, or hands
- Weakness in the muscles of the arms, shoulders, or hands; patient may have difficulty grasping and holding on to items
- Imbalance and other coordination problems; patient may have difficulty walking or may fall down, as the body is unable to follow through with what you are trying to do
- Loss of fine motor skills; difficulty with handwriting, buttoning a shirt, picking up coins, or feeding yourself
- Pain or stiffness in the neck
Acute myelopathy can develop quickly as a result of a spinal injury, spinal infection, inflammatory disease, radiation therapy, or neurological disorders.

MRI is the most informative examination for myelopathy. It also excludes other causes for the symptoms similar to those of stenosis, such as tumor, motor neuron disease, or multiple sclerosis. MRI is the best way to show the degree, extent, and site of cord compression, as well as the shape of the cord, and the extent of scarring or edema (Figure 8). The presence of increased signal in the cord does not necessarily correlate accurately with a less favorable outcome, as it can be the result of edema or scarring.

![MRI Image](image.png)

**Figure 8** Patient in her 70's presented with progressive lower limb weakness and unsteady gait, as well as upper limb weakness and numbness; sagittal T2-weighted image shows degenerative disc disease at multiple levels; at C5-C6, large disc bulging into anterior aspect of spinal canal; low signal behind the cord at same level, which is thickened ligamentum flavum; combination of disc bulge and thickened ligament resulted in severe spinal stenosis with compression of spinal cord; abnormal high signal in cord (yellow arrow) indicates that compression has resulted in myelopathy

The aim of any treatment is to improve the neurological impairment due to the myelopathy. Often, the best result of treatment is merely to halt the progress of the condition and to prevent further cord damage. Nonsurgical treatment for myelopathy may include bracing, physical therapy, and medication. These treatments can be used for mild myelopathy, and are aimed at reducing pain and helping patients return to their daily activities. Nonsurgical treatment does not remove the compression. Symptoms progress, usually gradually, but sometimes acutely. Some progression of symptoms can be irreversible, even with treatment, but it is important to stop any progression when identified in the mild stages. Some patients improve spontaneously, even after a period of deterioration, while others just stop getting worse at a given time and stabilize. This occurs presumably because, in these cases, the stenosis does not progress further due to one of the natural outcomes of osteoarthritis. Osteoarthritis tends to lead to an increasing stiffness which, in the end, results in a spontaneous cessation of movement at the affected levels in the neck. The percentage figure given for this cohort of patients who improve or stabilize without surgery varies between 30% and 60%. These patients usually have a mild degree of myelopathy, a long history of the condition, or a slow progress of the impairment. Non-surgical treatment may also be a consideration because many patients with cervical spondylotic myelopathy are elderly, and may suffer from significant co-morbidities. This would increase the risk of surgery to an
extent that a more conservative approach would have to be considered until such time as the risks of not operating exceed the risks of operating.

Surgery is the most reliable way of removing the compression on the spinal cord. Factors which would justify an operation include:

- Severe disability
- Relentlessly progressive course (40%-75%)
- Rapid deterioration of the myelopathy
- Significant instability between two vertebrae on flexion-extension x-rays
- More marked narrowing of the canal on imaging (>30% narrowing)
- “Banana” shaped deformity of the cord on MRI
- Marked increased signal in the cord on MRI, markedly abnormal somato-sensory evoked potentials
- Absence of contra-indication, such as significant co-morbidity and substantial remaining life-expectancy

However, many of the factors mitigating towards surgery may also indicate a less than satisfactory outcome, namely severe pre-operative deficit, abnormal signal in the cord, spinal cord atrophy, and severe radiological cord compression.

Spinal decompression surgery is a common treatment for myelopathy to relieve pressure on the spinal cord. Surgery can also be used to remove bone spurs or herniated discs, if they are found to be the cause of myelopathy. For advanced myelopathy caused by stenosis, a surgical procedure to increase the channel space of the spinal cord, called a laminectomy, may be recommended. This is a motion-sparing procedure, which means that the spinal cord retains flexibility at the site of the compression. An alternative to laminoplasty is decompression and spinal fusion, in which vertebrae are fused to eliminate motion in the affected segment of the spine.

**Degeneration of Cervical Spine and Discs**

**Osteoarthritis**

Cervical osteoarthritis is a condition marked by degeneration and breakdown of the cartilage between the facet joints in the cervical spine. This condition may result in the formation of osteophytes. Symptoms of this cervical arthritis may include pain that refers to the shoulder or between the shoulder blades, which feels worse at certain times of the day or night, but calms with rest.
Osteophytes

Osteophytes, or bone spurs, are smooth structures that can grow on bones and cause enlargement of joints. In the cervical spine, they are often found in the joints of Luschka, which are the small, stabilizing facet joints that are located between and behind the adjacent cervical vertebrae. Bone spurs tend to occur in adults over 60 years of age. Patients with cervical bone spurs may or may not have symptoms, including neck pain, and/or referred pain and weakness in the arms and legs. Their presence does not necessarily mean that they are the cause of the patient’s pain, as bone spurs are simply radiographic findings indicating a patient has degeneration in the neck.

Over time, osteophytes can grow large enough to irritate nearby nerve roots. Their overgrowth in the joints of Luschka is one of the most common causes of foraminal stenosis, which is a narrowing of the intervertebral foramen through which the spinal nerves need to pass unimpeded (Figure 9).

Disc Degeneration

Cervical degenerative disc disease may be diagnosed when a cervical disc is the source of pain in the neck. This can occur from twisting or falling on the neck, but more likely is from years of day-to-day wear and tear on the cervical spine. Symptoms related to a degenerative cervical disc may include a stiff neck and/or numbness, tingling, and weakness in the neck, shoulders, and/or arms as a result of a cervical nerve that has been irritated or pinched by the degeneration. These symptoms may persist for several months and fluctuate in intensity. Patients with a degenerative cervical disc will typically begin with non-surgical treatment, such as pain medication, exercise, and physical therapy. If that treatment is ineffective, surgery to remove all or part of the problematic disc may be necessary.

Figure 9 T1-weighted sagittal image shows degenerative disc disease, osteophytes, and osteoarthritis of C5-C6
Acute Cervical Injuries

Trauma to cervical vertebrae occurs less often than cervical pain and other symptoms resulting from changes that occur with aging, such as the development of osteophytes and osteoarthritis. Approximately 3% of patients who present to the ER as the result of a motor vehicle accident or fall have a major injury to the cervical spine. Ten to twenty percent of patients with a head injury also have a cervical spine injury. Up to 17% of patients have a missed or delayed diagnosis of cervical spine injury, with a risk of permanent neurologic deficit after a missed injury of 29%. Most cervical spine fractures occur predominantly at two levels. One third of injuries occur at the level of C2, and one half of injuries occur at the level of C6 or C7. Our discussion of common cervical spine injuries and fractures is based on the Harris and Mirvis classification of acute cervical injuries.

Hyperflexion Injuries

Hyperflexion is the most common fracture mechanism in cervical injuries, while hyperflexion sprain injuries are injuries to the soft tissues of the spine without fracture (Figures 10-12). Subtle injuries to the soft tissues may be demonstrated on MRI. However, there is controversy regarding the meaning of soft tissue abnormalities that are detected only on MRI, as signal changes do not necessarily equate with structural failure. In trauma centers, up to 25% of all patients with neck injury have signal abnormalities on MR, with indeterminate significance.

Figure 10 Patient was involved in an MVA and complained of neck pain; findings included edema in the posterior soft tissues indicating a hyperflexion sprain injury (yellow arrows) and edema in the vertebrae of the lower C-spine and upper T-spine, indicating bone bruise as a result of axial loading (blue arrows)
Figure 11 Hyperflexion sprain with spinal cord injury; sagittal images show severe soft tissue injury of posterior paraspinal structures, especially at C5-6 level, where the interspinous ligament and ligament of flavum are ruptured; disruption of C5-6 disc, with migration behind C5; large amount of spinal cord edema; axial image show spinal cord injury, and absence of flow void in right vertebral artery, indicating thrombosis as a result of dissection; patient had no fracture, but a severe hyperflexion sprain with acute disc herniation, non-hemorrhagic spinal cord injury, and vertebral thrombosis

Figure 12 MRA confirms occlusion of right vertebral artery
Unilateral interfacet dislocation is due to a hyperflexion injury with rotation. The superior facet on one side slides over the inferior facet and becomes locked. This results in an anterior subluxation of the upper vertebral body, typically measuring approximately 25% of the AP diameter of the body. Simple unilateral facet dislocation is a stable injury, although 30% of patients may have an associated neurologic defect. MRI plays an important role in the diagnosis, in order to see if there is disc extrusion leading to cord compression (Figure 13).

Figure 13 Unilateral interfacetal dislocation- MRI findings show a spinal cord lesion, which can be described as contusion, edema, or non-hemorrhagic spinal cord injury; rupture of the spinous ligaments and the ligamentum flavum; rupture of the disc with migration of disc material on the posterior side of C4 and anterior side of C5; disc space is always disrupted in this kind of injury due to the extreme rotation.
Bilateral interfacetal dislocation is the result of extreme hyperflexion. There is anterior dislocation of the articular masses, with disruption of the posterior ligament complex, posterior and anterior longitudinal ligaments, and the disc. When the dislocation is complete, the dislocated vertebra is anteriorly displaced one-half of the AP diameter of the vertebral body. Because of its extensive soft tissue damage and dislocated facet joints, this dislocation is unstable and is associated with a high incidence of cord damage (Figures 14-16).

Figure 14 Bilateral interfacetal dislocation; sagittal images show soft tissue swelling anteriorly, disruption of the disc, and non-hemorrhagic cord injury; axial image on right shows cord injury located in the grey matter, which is more sensitive to damage

Figure 15 Bilateral interfacetal dislocation; in order to regain normal alignment, progressive weights are used to lengthen the spine until reduction is achieved, under fluoroscopy; someone is holding the neck while more weight is added, so an actual “clunk” can be felt in the neck indicating that reduction is achieved; the facets started to move with 60 pounds, but full reduction, in this case, required 110 pounds
Figure 16 Bilateral interfacetal dislocations; images on left from wrestling injury show a 50% anteroposition of C3 on C4, with complete disruption of the posterior complex; patient had severe neurologic deficit; image on right shows complete transection of the cord, which is a very uncommon finding.

Flexion teardrop fractures are the result of a combination of flexion and compression, usually as a result of a motor vehicle accident. The teardrop fragment comes from the anteroinferior aspect of the vertebral body. The larger posterior part of the vertebral body is displaced backwards into the spinal canal. Seventy percent of patients have neurologic deficit. This is an unstable fracture associated with complete disruption of ligaments and anterior cord syndrome (Figures 17, 18).

Figure 17 Flexion teardrop fracture after striking head while diving into a swimming pool; CT shows fracture of body of C4; fracture of body of C5 with small fragment anteriorly; vertical orientation of fractures of bodies of C4 and C5 indicate that there was severe axial loading; propulsion of bone fragment of C5 anteriorly (teardrop) and larger portion of C5 vertebral body posteriorly against the spinal cord.
Hyperextension Injuries

A whiplash injury is one type of hyperextension injury. These injuries commonly occur due to rear-end traffic collisions, or poorly performed tackles in contact sports, such as football or rugby. They are usually considered to be neck strains, as the sudden force and backward jerking of the neck stretches and tears the neck’s muscles and tendons. Tendons are the bands of tissue that connect muscles to bones. A neck sprain can occur from a whiplash injury if ligaments are torn, which are the tissues that connect bones to each other. A cervical sprain from whiplash may involve the anterior longitudinal ligament of the spine.

In more severe cases, fractures of any of the cervical vertebrae can occur, as they are suddenly compressed by rapid deceleration. The worst-case scenario for a whiplash injury would involve dislocation or subluxation of the cervical vertebrae, especially at higher levels. If the body of C2 moves anteriorly with respect to C3, the spinal cord may become involved, resulting in quadriplegia or death. More commonly, subluxation occurs at the C6/C7 level.

The Hangman’s fracture is the most common cervical spine fracture. The hangman would place the knot under the subject’s chin to produce maximal extension-force. Its name originates from the mechanism by which it is most commonly created, as a result of the sudden deceleration that occurs in hanging. Technically, it is a traumatic spondyloolisthesis of the axis (C2), in which the axis slides forward over the C3 vertebrae (Figure 19). The Hangman’s fracture also involves a bilateral fracture of the pars interarticularis or isthmus and/or adjacent articular processes. This fracture accounts for 4-7% of all cervical fractures or dislocations, with their most frequent numbers in fatal traffic accidents, but also common in diving accidents. Although considered an unstable fracture, it seldom is associated with spinal injury, since the anteroposterior diameter of the spinal canal is greatest at this level, and fractured pedicles allow decompression. When associated with unilateral or bilateral facet dislocation at the level of C2, this type of Hangman’s fracture is unstable and has a high rate of neurologic complications.
The classifications of Hangman’s fractures include:

- **Type I (65%)** – hair-line fracture, C2-3 disc normal
- **Type II (28%)** – displaced C2, disrupted C2-3 disc, ligamentous rupture with instability, C3 anterosuperior compression fracture
- **Type III (7%)** – displaced C2, C2-3 bilateral interfacet dislocation, severe instability

![Figure 19 CT images of a Hangman’s fracture; fracture lines run through the pars interarticularis, resulting in a traumatic spondylolysis, which is a defect or stress fracture in the pars interarticularis of the vertebral arch; in this case, there was no neurologic deficit, as the spinal canal is widened at the level of the fracture](image-url)
When elderly people fall on their backs, they are at risk for hyperextension injuries with superimposed spondylosis, or spinal degeneration issues (Figure 20). Spondylosis leads to narrowing of the spinal canal, so a low velocity injury can lead to spinal cord injury. A disc space is often widened anteriorly and narrowed posteriorly, which is termed “an open book”. This is a sign of a hyperextension injury.

Figure 20 90-year-old male who fell on his back and back of his head, experiencing immediate quadriparesis after the event with no loss of consciousness; CT images on left display small black dots in the injured disc space, which are the result of negative pressure that causes a vacuum phenomena; hyperdensity posteriorly at C5-C6 could be a herniated disc or pre-existing disc degeneration; MR images on right show a subtle increase in signal intensity of spinal cord; these patients often have a central cord injury, and experience disproportionate weakness of their arms, and normal strength in their legs; injuries can be devastating, although it is uncommon that they are hemorrhagic

Figure 21 Hyperextension injury on MR displays injured disc with high signal on left; prevertebral soft tissue swelling in image on right
An extension teardrop fracture occurs when the anterior longitudinal ligament pulls a bony fragment away from the inferior aspect of the vertebra due to sudden hyperextension (Figure 22). The fragment is a true avulsion, in contrast to the flexion teardrop fracture, in which the fragment is produced by compression. This type of fracture is commonly seen in diving accidents, and tends to occur at lower cervical levels. It may also be associated with the central cord syndrome due to buckling of the ligamenta flava into the spinal canal during the hyperextension phase of injury. This injury is stable in flexion, but highly unstable in extension.

![Figure 22 Anterior soft tissue injury confirms that this is a hyperextension injury](image)

**Fractures Due to Axial Loading**

A Jefferson fracture (or Jefferson burst fracture) is caused by a compressive downward force that is transmitted evenly through the occipital condyles to the superior articular surfaces of the lateral masses of C1. This process displaces the masses laterally, and causes fractures of the anterior and posterior arches, along with possible disruption of the transverse ligament. A Jefferson fracture can occur after diving into excessively shallow water, or a vertical fall onto an extended neck. Since the vertebral foramen is large in the superior cervical area, it is unlikely that there will be damage to the spinal cord at the C1 level. However, there may be damage further down the vertebral column.

Burst fractures can also occur in the lower cervical spine. Both the Jefferson fracture at C1 and the lower burst fractures are considered unstable fractures.
Additional Injuries

Odontoid or dens fractures constitute approximately 40% of the fractures of the axis. They are seen in the elderly, but also frequently in children (75% of cases), due to their relatively large head-to-spine ratio. Dens fractures are most commonly caused by traffic collisions and falls. The Anderson & D’Alonzo Classification is seen below (Figure 23):

- **Type I** – Avulsion of the tip of the dens where it is attached to C1; rare fracture, but stable, as fracture line is above the transverse ligament
- **Type II** – Through the base of the dens, which is the most common fracture; always unstable and heals poorly
- **Type III** – Fracture through the body of the axis and sometimes facets; can be unstable, but has better prognosis than Type II due to better healing of the fracture, which runs through the metaphyseal bone of the body of C2

Figure 23 Classifications of odontoid (dens) fractures
Dens fractures are often at higher risk for avascular necrosis, due to the isolation of the distal fragment from any blood supply. These fractures often take a long time to heal, and, as with any fracture of the vertebral column, there is a slight risk of spinal cord involvement (Figures 24, 25).

Figure 24 Sagittal MR images demonstrate fracture through the base of the odontoid; prevertebral soft tissue swelling; rupture of interspinous ligament; displacement of cord by epidural fluid collection, which could be blood or CSF due to arachnoid rupture.

Figure 25 Axial MR images on same patient as above with fracture through the base of the odontoid; cervical spine on left, and thoracic spine on right; epidural fluid collection located posteriorly on thoracic, resulted from T-spine fracture.
Atlanto-occipital dissociation injuries are characterized by complete disruption of all ligaments between the atlas and occiput, with subluxation or complete dislocation of the atlanto-occipital facets (Figure 26). Death usually occurs immediately from stretching of the brainstem, which causes respiratory arrest. Although it is considered an uncommon injury, it is reported to occur in 31% of fatal motor vehicle accidents, and is more common in children due to their larger heads. Up to 50% of atlanto-occipital dislocations are overlooked initially, which can have catastrophic results, as cervical traction can be fatal.

Figure 26 Sagittal images of atlanto-occipital dissociation; notice the prevertebral hemorrhage and compression on the cord

Tumors and Diseases of the Cervical Spine

Tumors, or neoplasms, of the cervical spine can be categorized as metastatic or primary. Metastatic tumors are the most common tumors of the spine. Primary tumors of the spine can be benign or malignant, and can be further subdivided into extradural and intradural neoplasms. Extradural tumors are often the neoplasms that infiltrate the bony structure of the vertebrae, as they are outside the dural covering of the spinal cord. Intradural means that the tumor is arising from or within the dural sac, which contains the spinal cord and nerves. Intradural tumors are further classified as intramedullary or extramedullary, indicating whether or not a tumor is arising from inside the dural covering, and within the spinal cord itself (intradural-intramedullary), or from inside the dural covering, but not within the spinal cord (intradural-extramedullary). Overall, primary spine tumors are rare, and comprise approximately .04% of all tumors, and 10% of all bone tumors.
Metastasis

The spinal column is one of the most common sites for metastasis. Metastatic tumors are routinely treated without surgery, unless there is resultant spinal instability or neurologic compromise. The majority of metastatic lesions are treated with chemotherapy and/or radiation therapy that is specific for the primary cancer type. Metastases to the spine often involve the vertebral bodies (Figures 27, 28). Primary malignant vertebral body tumors, which include chondrosarcomas and chordomas, are less common.

Figure 27 Sagittal image demonstrates a C6 vertebral body metastasis from alveolar soft part sarcoma, a rare, slow growing, highly angiogenic tumor that is most frequently found in young adults, and often begins in the lower extremities.

Figure 28 40-year-old male presenting with headache, confusion, dyskinesia, and reduced level of consciousness; sagittal T1-weighted image with contrast and fat sat reveals large cystic/solid enhancing cervical tumor mass; evidence of extensive leptomeningeal tumor spread, including around the cerebellum; low signal in upper cervical vertebral bodies, which is a typical post-radiation therapy appearance; patient has prior history of ganglioneurocytoma of cervical spine diagnosed 2 years earlier, treated with multiple resections and radiation therapy.
Primary Benign Extradural Tumors

Osteochondroma

Osteochondromas represent the most common bone tumors, and are developmental lesions, rather than true neoplasms. They constitute 20%-50% of all benign bone tumors, and 10%-15% of all bone tumors. They typically develop during childhood, in the period of most rapid skeletal growth, but once formed, they remain for the rest of the individual’s life. Osteochondromas are primarily a part of the growth plate, which separates and continues growing independently, without an associated epiphysis, usually away from the joint. The medullary cavity is continuous with the parent bone, with an overlying hyaline cartilage cap. Osteochondromas commonly arise from the appendicular skeleton, especially around the knee. The posterior elements of the spine are uncommon, but not rare sites for these lesions. Osteochondromas may be solitary or multiple, with the latter being associated with the autosomal dominant syndrome hereditary multiple exostoses (HME). Complications associated with osteochondromas are more frequent with HME, and include deformity (cosmetic and osseous), fracture, vascular compromise, neurologic sequelae, overlying bursa formation, and malignant transformation. Malignant transformation is seen in 1% of solitary osteochondromas, and in 3%-5% of patients with HME. Continued lesion growth, and a hyaline cartilage cap greater than 1.5 cm in thickness, after skeletal maturity, suggest malignant transformation. Symptomatic presentation is either due to mechanical effects of the lesion, fracture, or malignant transformation. If malignant transformation does occur, the resultant chondrosarcoma is usually of low grade (67-85% of cases), and surgery is usually curative (79-90%).

MRI is the best imaging modality to assess cartilage thickness (thus assessing for malignant transformation), the presence of edema in bone or adjacent soft tissues, and visualizing neurovascular structures in the vicinity (Figure 29). The cartilage cap of osteochondromas appears the same as cartilage elsewhere, with intermediate to low signal on T1, and high signal on T2-weighted images. With gadolinium contrast administration, enhancement of benign lesions is normally seen in the tissue that covers the cartilaginous cap, which is fibrovascular in nature. However, the cartilaginous cap itself should not enhance.

Figure 29 20-year-old male with radiculopathy and left upper limb weakness following trauma; sagittal T2-weighted image on left shows lesion that is heterogeneous in signal intensity, and mildly hyperintense compared to muscle; sagittal T1-weighted image with contrast and fat sat in center shows that lesion does not enhance; axial T1-weighted image with contrast and fat sat on right displays the mass causing significant mass effect on the spinal cord at the level of C5-C6, deviating the thecal sac and cord to the right, obliterating surrounding CSF signal; no associated cord or bone edema signal changes are observed
Additonal primary benign extradural tumors that may be found in the cervical spine include, but are not limited to, osteoid osteomas, osteoblastomas, aneurysmal bone cysts, hemangiomas, giant cell tumors, and eosinophilic granulomas.

**Primary Malignant Extradural Tumors**

**Multiple Myeloma**

Multiple myeloma originates in malignant plasma cells that infiltrate red bone marrow. Plasma cells live in the bone marrow in the center of the bones, and are a type of white blood cell, which are key players in attacking germs and other harmful invaders that enter the body. However, when plasma cells become cancerous, their typical protective properties no longer work. Multiple myeloma usually occurs in bone marrow with the most activity, which includes marrow in the spine and pelvic bones. When plasma cells develop into myeloma cells, they can produce a malignant tumor called a plasmocytoma. This may occur as one solitary tumor, but “multiple” myeloma means more than one tumor exists. Multiple myeloma is the third most common blood cancer in the United States and is the most common primary malignant bone neoplasm in adults. It typically occurs in adults over age 50, and is more common in men and African Americans.

One of the main features of multiple myeloma is that the malignant cells produce a large amount of abnormal antibodies in the blood called M proteins. These M proteins are of no benefit to the body, and crowd out the healthy plasma cells that are beneficial. When the cancerous cells outnumber the healthy cells, bone damage and other symptoms occur. Healthy bones regularly go through a break-down and build-up cycle called remodeling, which keeps bones strong. The cells responsible for remodeling are osteoclasts, which break down old bone, and osteoblasts, which build new bone. Myeloma cell growth interferes with the way osteoclasts and osteoblasts normally work together, because the myeloma cells signal the osteoclasts to speed up the dissolving of bone. At the same time, the myeloma cells overpower the osteoblasts, preventing the formation of new bone. As a result, spinal bones become soft and weak, making them painful and susceptible to fractures and osteoporosis. The increased breakdown of bone can also cause spinal cord compression and hypercalcemia. Multiple myeloma can impact many areas of the body, and can cause significant problems in the spine. It can cause back pain, osteoporosis, spinal fractures, and spinal cord compression. It does not yet have a cure, but many treatment options are available.
MRI is generally more sensitive in detecting multiple lesions compared to plain film skeletal surveys. Infiltration and replacement of bone marrow are quite well visualized, especially when whole body scans are performed. Signal characteristics of multiple myeloma on MRI are typically low signal on T1, with high-grade diffuse involvement becoming isointense to adjacent normal marrow. It has high signal on T2 with fat suppression, and is hyperintense on T1 with contrast (Figures 30, 31).

Figure 30 Sagittal T1-weighted image on left, sagittal T1-weighted image with contrast in center, and sagittal T2-weighted image on right display a sizable enhancing mass that is expanding and destroying the posterior elements of the C3 vertebral body; this results in spinal narrowing, compression, and displacement of the spinal cord.

Figure 31 Sixty-year-old female with history of multiple myeloma, has worsening mechanical neck pain, increased arm and leg weakness with numbness and gait difficulties; left and center images display large C5-C6 epidural tumor causing severe spinal cord compression and kyphotic deformity; image on right is 6 months post-op, showing satisfactory decompression of the spinal cord; surgery involved anterior C4, C5, and C6 corpectomy (removal of all or part of vertebral body), with posterior stabilization.
Chordomas

Chordomas are rare, low-grade malignant tumors arising from notochordal remnants of the axial skeleton. They are typically locally aggressive, radio resistant, and slow-growing, but they have a high propensity for local recurrence. The most common sites are the sacrum and clivus, with the upper cervical region representing the second most common site in the spine. Total removal is the technique of choice to improve the prognosis, but with the existence of adjacent critical anatomical structures, it is sometimes impossible to achieve wide-margin resection without sacrificing vital structures, potentially causing severe morbidity or mortality. Chordomas of the “mobile” portion of the spine (such as the cervical region) have a poor prognosis, and traditionally, have been difficult to manage. However, earlier diagnosis of smaller lesions, which is aided by MRI, may have a significant impact on their management and prognosis.

Among primary malignant tumors of bone, chordoma appears to be the fourth most frequent histological type (after osteosarcoma, chondrosarcoma, and Ewing’s sarcoma), accounting for 3% to 4%. The most common sites for the development of chordoma are the skull (32%), spine (33%), and sacrum (29%). Median age at diagnosis is 58.5 years, with a generally progressive increase in incidence with age. Spinal chordomas frequently produce compression of the spinal cord and nerves with pain, loss of mobility, and sensory motor deficit. Cervical chordomas tend to present as a pharyngeal or lateral neck mass. As the tumor expands, atypical presentations such as dysphonia or dysphagia are reported. The possibility of a chordoma should be considered when a destructive lesion of the cervical vertebral body is associated with a large well-defined soft tissue mass that is extremely hyperintense on T2-weighted images, and presents inhomogeneous enhancement after contrast injection. MRI detects epidural spread, and can be used to evaluate encasement of the vertebral arteries before surgery.
Current management of spine chordoma involves surgery, radiotherapy, or both. Surgical management of malignant cervical spine tumors can be challenging, depending on tumor location, tumor consistency, and clinical symptoms. Surgery with complete tumor resection is considered the treatment of choice. However, total resection is challenging due to the proximity of vital structures (vertebral arteries, spinal cord, and cervical nerve roots). In some cases, a pre-operative angiogram may be helpful in determining the proximity of the chordoma to the vertebral arteries. If one of the vertebral arteries is encased in tumor, a pre-operative test occlusion with subsequent embolization and sacrifice of the vessel may allow for gross total resection of the tumor (Figure 32). Chordomas are considered to be radioresistant tumors and local control can only be achieved with high radiation doses. Proton beam radiation therapy offers the advantage of increasing the dose delivered to the tumor, while minimizing radiation to surrounding normal tissues. Radiotherapy is often reserved for chordomas of the cervical spine that involve incomplete removal, recurrences, and inoperable tumors. Five-year overall survival rates are 60%-70%, with 10-year overall rates at 35%-40%. Tumor recurrences typically occur in the form of multiple bone masses. Chordomas most often metastasize to lymph nodes, lung, bone, and liver.

Figure 32 82-year-old man with 3-month history of progressive motor deficit without dysphagia or dysphoria; large, firm, and immobile mass involving right side of middle anterior cervical region; T2-weighted sagittal image on left show lesion involving anterior and right lateral portion of C5-C6 with marked retropharyngeal and epidural space involvement, with anterior cord compression; T1-weighted post-contrast image in center shows inhomogeneous enhancement of the lesion with posterior extension which encased the right vertebral artery (red arrow); lateral cervical radiograph on right demonstrates anterior reconstruction with expanded cage and C4-C7 anterior plating

Additional primary malignant extradural tumors of the cervical spine include, but are not limited to, solitary plasmacytomas, osteosarcomas, chondrosarcomas, Ewing’s Sarcomas, and lymphomas.
Intradural-Extramedullary Tumors

Spinal Schwannomas

Schwannomas are usually benign nerve sheath tumors composed of Schwann cells, which normally produce the insulating myelin sheath covering peripheral nerves. Spinal schwannomas arise from nerves within the spinal canal. They are the most common intradural extramedullary spinal tumors, representing 30% of such lesions, and are most frequently seen in the cervical and lumbar regions. Patients commonly present with pain, and radicular sensory changes, as spinal schwannomas usually arise from the dorsal sensory roots. Myelopathy may occur if the lesion is large. Most spinal schwannomas are solitary and sporadic. However, there is an association with neurofibromatosis type 2. Schwannomas are slow growing lesions, but can be debilitating. They almost never undergo malignant change. Surgery is usually the treatment of choice. On MR imaging they are typically solid and well-defined lesions with low T1 and high T2 signals, showing contrast enhancement. The signal intensity can be heterogeneous due to associated hemorrhage, intrinsic vascular changes, cyst formation, and fatty degeneration.

Figure 33 60-year-old female with 2 week history of increasing neck and right arm pain; sagittal T1 fatsat with contrast on left shows intradural-extramedullary mass (schwannoma) with mildly expanded spinal canal at C2 and C3; image in center shows enhancing extra-axial mass, compatible with globular meningioma, partially imaged posteriorly; image on right demonstrates how extramedullary mass (*) markedly displaces and compresses the cord (blue dotted line) to the left.
Spinal Meningiomas

Meningiomas arising from the coverings of the spinal cord represent a minority of all meningiomas (approx. 12%), but are the second most common intradural extramedullary spinal tumor, representing 25% of all such tumors. Although they are usually small, they can result in significant neurologic dysfunction due to the confines of the spinal canal. Spinal meningiomas have a peak incidence in the fifth and sixth decades, and in the adult population, females are approximately ten times more commonly affected than males. Most patients present with motor deficits as a result of compression of the spinal cord. The majority of spinal meningiomas are benign, with greater than 95% being classified as WHO (World Health Organization) grade I lesions, although clear cell meningiomas (a grade II histological variant) have a predilection for the spine. Spinal meningiomas are not distributed evenly along the spinal canal, with 15% found in the cervical spine, 80% in the thoracic spine, and an uncommonly low percentage in the lumbosacral region. On MRI meningiomas typically appear isointense to slightly hypointense on T1, isointense to slightly hyperintense on T2.

![Figure 34 18-year-old male with gradually worsening quadriplegia; intense homogeneous enhancement of well defined meningioma in intradural extramedullary location on T1 fatsat images after contrast injection; sagittal image on left, coronal in center, axial on right; right side location of lesion causing cord compression and displacement to the left](image)

Neurofibromas are also classified as benign intradural-extramedullary tumors of the cervical spine.

Ependymomas

Ependymomas are primary tumors, beginning in either the brain or spine, and can be classified as both extramedullary and intramedullary tumors. Ependymal cells are one subtype of glial cells in the central nervous system, along with astrocytes and oligodendrocytes. It is believed that ependymomas develop from precursor cells to ependymal cells, which line the ventricles and the central canal of the spinal cord. The World Health Organization classifies ependymomas into grade I, which are slow-growing with long-term survival, grade II ependymomas, which are a low-grade variety, and a more malignant type called anaplastic ependymoma, which are grade III. The CERN Foundation, which is the Collaborative Ependymoma Research Network, states that all grades of ependymoma tumors are considered cancer. Like other primary brain and spinal cord tumors, these cancers tend not to spread to other parts of the body, but can recur and require treatment. Ependymomas are the third most common form of childhood brain and spine tumors, with most occurring in young infants and children. The majority of ependymomas in children occur in the brain, while the majority of adult ependymomas occur in the spine. Spinal ependymomas are the most common intramedullary neoplasm in adults, and the most
common spinal cord tumor overall. The cervical spinal cord is the most common site (44%). Peak incidence is in the fourth decade, with males more commonly affected. Clinical presentation typically includes pain, weakness, and sensory changes. Dominant motor symptoms are commonly associated with very large ependymomas.

MRI is the modality of choice for evaluating suspected spinal cord tumors such as ependymomas. Features may include a widened spinal cord, a well-circumscribed (although not encapsulated) tumor, tumoral cysts (22% of cases), and average length of four vertebral body segments. Most ependymomas are isointense to hypointense on T1 images, with mixed signal lesions if cyst formation, tumor necrosis, or hemorrhage has occurred. On T2-weighted images, they are hyperintense, with peritumoral edema in 60% of cases. Associated hemorrhage leads to the “cap sign”, which is a hypointense hemosiderin rim on T2, found in 20-33% of cases. The cap sign is suggestive of ependymoma, but also seen in hemangioblastomas and paragangliomas. On T1-weighted images with contrast, almost all ependymomas enhance strongly, although somewhat inhomogeneously.

Figure 35 Sagittal T2 image on left is a 45-year-old male with gradual upper limb weakness; enhancing mass is present within the substance of the cervical cord at the C5 level; it is surrounded at either end by dilated cystic spaces which may represent a tumor syrinx rather than part of the mass itself; faint signal drop on T2-weighted image which may represent peripheral blood product; sagittal T2 image on right is a 65-year-old female with 18 months of neck pain radiating down to right arm; displays a centrally located intramedullary mass in upper cervical spinal cord extending between C2/3 and mid C4 levels; associated cord expansion is noted; an associated tumor syrinx extends between C1/2 and the lower C4 vertebral levels; at inferior aspect of syrinx is low T2 signal compatible with a hemosiderin cap
Intradural-Intramedullary Tumors

Gangliogliomas

Gangliogliomas are composed of two cell populations—ganglion cells, which are the large, mature neuronal elements, and a neoplastic glial element. The proportion of each component varies widely, and it is the grade of the glial component that determines biological behavior. Spinal gangliomas are rare, comprising 1.1% of all spinal cord neoplasms. They represent 15% of intramedullary neoplasms in the pediatric age group. Occurring predominantly in children and young adults, the mean age of presentation is 19 years, with no gender predilection. Clinical presentation is similar to that of other intramedullary spinal tumors, with pain, weakness, and sensory changes being common.

Gangliomas of the spinal cord typically involve long segments of the spinal cord, often extending for greater than eight vertebral body segments. They are commonly not located centrally in the spinal cord. Approximately half of these tumors contain tumoral cysts. Signal characteristics on MRI include a mixed signal intensity on T1-weighted images, due to the dual cellular elements of these tumors. This is a unique finding among spinal cord tumors. On T2, gangliogliomas display high intensity, with surrounding edema being an uncommon finding. On T1 with contrast, most tumors demonstrate patchy enhancement; however, up to 15% of cases may demonstrate no enhancement. Calcification is common in gangliogliomas, which will appear as areas of low signal with blooming on gradient echo sequences.

Gangliogliomas are generally slow growing. Gross resection of the tumor is recommended. However, despite their low grade, there is a 27% rate of recurrence, which is approximately three to four times that of cerebral gangliogliomas. This is likely due to the increased difficulty of complete surgical excision of spinal tumors. Overall, there is an 89% 5-year survival rate after resection.

Figure 36 Adult male with gradual upper and lower limb weakness and sensory changes; T2-weighted sagittal image on left displays expanded upper cervical cord (opposite C1 and C2) by an eccentric mass (yellow dashes) with higher signal intensity than spinal cord; mass was iso-intense to cord on T1-weighted images, and did not demonstrate convincing contrast enhancement; evidence of prior surgery (laminectomy and small biopsy) indicated by orange arrows on both images; T2-weighted axial image on right again displays eccentric location of mass (yellow dashes) within the spinal cord (blue star)
Hemangioblastomas

Hemangioblastomas are benign vascular lesions that do not undergo malignant degeneration. They are the third most common intramedullary spinal neoplasms, representing 2-6% of all intramedullary tumors. Two thirds of hemangioblastomas are considered sporadic, as they appear on their own, while one third of patients with hemangioblastomas (not limited to the spine) also have von Hippel-Lindau syndrome, in which they present earlier with multiple tumors. Peak presentation of hemangioblastomas is in the fourth decade, with males and females equally affected. Hemangioblastomas are rare occurrences in children. Clinical presentation is similar to that of other intramedullary spinal tumors, with pain, weakness, and sensory changes common. Rarely, spinal hemangioblastomas may cause subarachnoid hemorrhage or hematomyelia.

The most common location of spinal hemangioblastomas is the thoracic spinal cord (50%), followed by the cervical cord (40%). The majority of these lesions have an intramedullary component, with two-thirds located eccentrically (not in the center of the cord), and having an exophytic component, meaning they are growing outward from within the spinal cord towards the dorsum of the cord. Only 25% of hemangioblastomas are entirely intramedullary, with a minority that are entirely extramedullary, and a rare lesion that is extradural. Hemangioblastomas are slow growing, and are usually treated by surgical resection.

Hemangioblastomas usually appear as discrete nodules, but can be accompanied by diffuse cord expansion. An associated tumor cyst or syrinx is common (50-100%). MRI signal characteristics of the solid tumor components on T1-weighted images include hypo- to isointense lesions, which may be difficult to identify. Approximately 25% of lesions are hyperintense on T1, with variability relative to the normal spinal cord. On T2-weighted images, these lesions may be iso- to hyperintense, with focal flow voids seen in larger lesions. Surrounding edema and an associated syrinx are often seen. Hemosiderin capping may also be present, which involves a cap of T2 hypointense hemosiderin above and/or below the tumor, due to previous hemorrhage. These tumor nodules enhance vividly on T1-weighted images with contrast.

Figure 37 35-year-old male with upper limb weakness, increasing over a number of weeks with increased tone in legs; sagittal T2 image on left and STIR image on right show nodule within the cord at the level of C5, with adjacent peritumoral cysts and extensive cord edema; serpentine flow voids are noted posterior to the lesion.
Von Hippel-Lindau disease is characterized by numerous benign and malignant tumors in different organs (at least 40 types) due to mutations in the VHL tumor suppressor gene on chromosome 3. Tumors are most commonly seen in the abdominal cavity, or affecting the central nervous system. Most patients are diagnosed with their first tumor at age 26. Central nervous system hemangioblastomas occur in approximately 70% of patients. The incidence of spinal cord tumors is approximately 30%, most commonly in the cervical and thoracic cord.
Astrocytomas

Astrocytomas are rare tumors that arise from astrocytes in the spinal cord. Most are benign, low-grade tumors that are readily diagnosed with MRI. They typically cause the spinal cord to appear expanded, often with cysts and a variable enhancement pattern. Astrocytomas occur in the adult and pediatric populations, representing 30-35% of intramedullary spinal cord tumors in adults, and 90% of intramedullary tumors in children. Presenting symptoms typically evolve over months to years, with regional back pain as the most commonly reported initial complaint. Malignant tumors produce rapid neurological deterioration. A contrast-enhanced MRI is the best modality for diagnosis and evaluation of an astrocytoma, as it can delineate the extent of the tumor mass, the enhancement pattern of the tumor, spinal cord edema, and the presence of associated tumoral cysts and syringal cavities. Outcome for low-grade astrocytomas is less favorable than that of ependymomas with regard to both recurrence and function, though many have prolonged survival. Low-grade lesions are associated with the younger population, while adults mainly exhibit high-grade lesions. Malignant degeneration develops in 25% of adult astrocytomas. Outcome for high-grade tumors is extremely poor, as tumor progression is relentless.

Astrocytomas of the spinal cord vary in size and length, with the average length equal to 7 vertebral body segments. They are typically iso- or hypointense on T1-weighted images, and hyperintense on T2-weighted images. Enhancement with contrast is variable, with some astrocytomas remaining completely nonenhancing. Tumoral cysts are a common finding, and reactive cysts may be observed at the tumoral poles.

Figure 40 Sagittal T1-weighted contrast-enhanced image demonstrates a large tumor with heterogeneous enhancement; histology revealed a pilocystic astrocytoma
Oligodendrogliomas

Oligodendrocytes are the myelination cells of the brain and spinal cord. Oligodendrogliomas are one of the primary brain tumors usually occurring in the cerebral hemispheres, while these tumors of the spinal cord are rare. When in the spine, they are found most frequently in the thoracic area (30%) and cervical area (25%), frequently presenting with an intramedullary lesion in the spinal canal. On MRI, oligodendrogliomas are isointense on T1-weighted images, hyperintense on T2, and show heterogenous enhancement post-contrast. Microcalcifications are often seen, similar to intracranial oligodendrogliomas. Surgical resection is the treatment of choice, but gross total resection is often difficult due to these tumors having intramedullary locations. Tumor recurrence has been observed within 8 months to 2 years in approximately 42% of cases.

Figure 41 46-year-old male with progressive neck pain for a year; intramedullary mass 12.5 cm long, from C2 to T4 level; sagittal T1-weighted image with contrast on left demonstrates heterogeneously enhanced intramedullary tumor; T2-weighted image on right demonstrates hyperintense mass, with syringomyelia observed above the tumor

Figure 42 Same patient as above, contrast-enhanced sagittal T1-weighted images; image on left is 3 months post-op, showing small residual tumor located at C3-C5 level; image on right is 12 months post-op, with tumor recurrence surrounding the previous surgical field
**Teratomas**

Cervical teratomas are extremely rare germ cell tumors, which are the cells that develop into the embryo, and later become the cells that make up the reproductive systems of males and females. The majority of teratomas occur in the testes or ovaries, or the sacrococcygeal region. When these germ cell tumors occur outside of the gonads, they are known as extragonadal tumors, which is where cervical teratomas fit in. The exact cause of teratomas is unknown, and their appearance is sporadic. Most cervical teratomas have some type of relationship with the thyroid, and the clinical picture and prognosis between these tumors is the same. Many researchers classify all neck teratomas as cervical teratomas. The majority of these cervical tumors occur in newborns and children, and are benign. They account for 3-5% of all tumors in childhood. Small teratomas may be asymptomatic, but larger teratomas may cause disfigurement and compression of nearby structures, such as the trachea and esophagus. Compression of vital structures may cause life-threatening complications such as respiratory distress. In very rare cases, cervical teratomas occur in adults, where they are usually malignant. They may metastasize to nearby lymph nodes and other organs, especially the lungs. As in children, cervical teratomas in adults can compress nearby structures, resulting in respiratory distress and additional complications. Treatment of cervical teratomas typically involves surgical removal of the tumor and affected tissue. In cases that are diagnosed prenatally, surgery may be performed as soon as the baby is delivered via Cesarean section, with the baby remaining attached to the placenta for normal blood flow exchange. For adults, radiation therapy may be used before surgery to shrink the tumor, with chemotherapy following surgery if necessary. Infants with a benign cervical teratoma rarely experience recurrence of the tumor, while malignant cervical teratomas in adults recur more often.

MR signal characteristics are heterogeneous on both T1- and T2-weighted sequences, and are highly variable, dependent on tumor components. These masses usually have cystic, tissular, and fat components. Calcifications may be detected as magnetic susceptibility effects, and are identifiers for teratomas.

![Image](image_url)

**Figure 43** Cervical intramedullary immature teratoma with metastatic recurrence in an adult; sagittal MRI depicts the fusiform-shaped and eccentrically located intramedullary tumor at the C1-C2 levels, appearing hypointense on T1-weighted image on left, and mixed signal intensity on T2-weighted image on right, with adjacent spinal cord edema; white arrow indicates cystic lesion within the spinal cord distal to the mass; signal features were lacking typical characteristics of heterogeneous solid and cystic components, and presence of fatty tissue and calcification.
Figure 44 Same patient as above; image on left performed immediately post-operative shows T1-weighted contrast-enhanced sagittal MRI, with black arrowhead indicating gross-total removal of tumor; sagittal T1-weighted images with contrast in center and on right performed at 10-month follow-up reveal two metastatic extramedullary lesions at C4-C6 (center image) and T11-T12 (right image), appearing highly enhanced with heterogeneous features; it is presumed that a small malignant focus was disseminated by CSF before or during the initial surgery.

Figure 45 Prenatal images of a fetus with cervical teratoma (Images ©2011 Veronika Frisova)

Figure 46 Postnatal images of a baby with cervical teratoma; baby was delivered by Cesarean section at 33 weeks due to ruptured amniotic membranes, underwent surgical removal of tumor one week later (Images ©2011 Veronika Frisova)
PNET (Primitive Neuroectodermal Tumor)

PNETs are malignant neoplasms that generally arise from bone and soft tissues, with predilection for young adults. They share biologic and histologic features with Ewing’s sarcoma. Peripherally located tumors are called pPNET, which are the second most common soft tissue sarcomas in children. They are more common in males and Caucasians. The most frequent primary sites are the paravertebral region, chest wall, pelvis, and limbs. Clinical presentation depends on the affected site and the degree of tumor invasion. Due to the aggressive behavior of these neoplasms, and their great potential to metastasize, treatment should be multimodal, involving radical surgical resection, radiotherapy, and chemotherapy. Unfortunately, even with multimodal treatment, the prognosis is still poor, with disease-free survival rates at 45% after 7 years.

![Image 1](image1.jpg)

**Figure 47** 22-year-old female with history of severe progressive neck pain, more intense on the right side; post-gad sagittal T1-weighted image on left demonstrates intraspinal component compressing the spinal cord antero-laterally; post-gad axial T1-weighted image on right demonstrates intense enhancement of lesion in right posterior cervical region, with cervical spine extension

![Image 2](image2.jpg)

**Figure 48** Same patient as above, post-op images; sagittal T2-weighted image on left shows removal of intraspinal component of tumor; post-gad axial T1-weighted image on right demonstrates good decompression and no enhancement in cervical region
Figure 49 Same patient as above; patient underwent adjuvant therapy that included chemo and radiation for 12 months; post-gad sagittal and axial T1-weighted images show no post-treatment tumor re-growth, as there is an absence of contrast enhancement in the region previously occupied by the tumor; three months after completing adjuvant treatment, patient experienced symptoms of headache and vomiting, with CSF analysis positive for neoplastic cells; sadly, patient succumbed to this disease.

Additional intradural-intramedullary tumors of the cervical spine include, but are not limited to, lipomas, dermoids, epidermoids, neuroblastomas, cholesteatomas, and subependymomas.
Forestier Disease

Forestier disease is also known as diffuse idiopathic skeletal hyperostosis (DISH). It is a fairly common condition affecting elderly individuals, especially males in their sixth to seventh decades, characterized by bony proliferation at sites of tendinous and ligamentous insertions on the spine. On imaging, it is typically characterized by the flowing ossification of the anterior longitudinal ligament, particularly in the cervical and thoracic spines. Ossifications are usually noted along the anterior or right anterolateral aspects of at least four contiguous vertebrae, hence they are termed “flowing ossifications”. Disc spaces are usually well preserved. The etiology of DISH is unknown, but additional pathology includes paraspinal connective tissue and annulus fibrosis, degeneration of the peripheral annulus fibrosus fibers, anterolateral extensions of fibrous tissue, hypervascularity, chronic inflammatory cellular infiltration, and periosteal new bone formation on the anterior surface of the vertebral bodies.

Figure 50 MR images of a 60-year-old male with neck and left arm pain; both images show florid flowing ossifications along the anterior aspects of the cervical vertebrae, with well preserved disc spaces; T1-weighted image on right shows increased intra-discal signal at C6/7, which could represent intra-discal calcification
**MRI Coils for Cervical Spine Imaging**

Coils appropriate for cervical spine imaging are supplied with each of Hitachi’s MRI systems. Proper patient positioning and immobilization, along with isocenter or near-isocenter positioning of the selected coil, will result in excellent quality cervical imaging.

The Oasis is a vertical field magnet, and is equipped with laser lights for positioning purposes in all three planes or directions: head-to-foot (horizontal plane), right-to-left (longitudinal plane), and anterior-to-posterior (coronal plane). The Echelon OVAL and the Echelon systems are both horizontal field magnets, which have laser lights for positioning purposes in the longitudinal and horizontal planes.

**Oasis Open MRI System**

Proper patient positioning, with both the coil and the anatomy at isocenter in all three planes, results in improved image quality on the vertical field Oasis 1.2T Open MRI system. Body habitus will play a key role in both coil selection and table pad choices on the Oasis system. The coil of choice for cervical spine imaging is the RAPID cervical coil. One must remain aware of how the use of trough pads, table pads, or no pads will affect the coronal positioning of both the patient and the coil. Hitachi also offers an extensive inventory of accessory pads and sponges for patient stability, comfort, and safety. The cervical coil should be as close as possible to the center of the laser lights in all three directions: head-to-foot (axial or transverse plane), right-to-left (sagittal plane), and anterior-to-posterior (coronal plane). When positioning the coil on the Oasis patient table, the center of the coil must be between the red arrow markings on the table and the end of the patient table nearest the magnet.
Coils and Positioning

- 8-Channel RAPID Cervical Coil

- 8-Channel CTL Spine Coil

- 1-Channel Solenoid Coil
RAPID Cervical Coil

The coil of choice for a study of the cervical spine on the Oasis is the RAPID cervical coil, which is a standard coil with the Oasis system. Pad A should be placed on the patient table at the end of the table closest to the magnet, with additional table pads placed as needed for patient comfort. The base of the RAPID cervical coil is then placed on top of pad A, with the horizontal center mark on the base of the coil between the marking on the patient table and the end of the table nearest the magnet. Positioning the cervical coil on top of pad A allows for optimal alignment of the coil in the A-P, or coronal, direction, as well as better alignment with the patient’s cervical spine, which lies more posteriorly in the body. The patient should be positioned in the coil with their shoulders in contact with the bridge piers, and the cervical spine in a midline position. The bridge of the coil is then attached to the base of the coil. Sponges and pads should be used to immobilize the patient in the cervical coil. The transaxial and sagittal laser lights should be centered on the patient’s hyoid bone, which approximates the location of C3. Centering of the laser lights should be performed to the patient’s anatomy, rather than to the centering marks on the bridge of the coil.

The RAPID cervical coil can be used without the bridge in place, if absolutely necessary in order to complete the patient’s exam; however, image quality will be compromised. Protocols have been developed for use of the RAPID cervical coil with no bridge, and are available in the System Directory. Additionally, for patient safety, connector cover plates must be inserted in the receptacles where the bridge of the coil is normally attached. Additionally, the RAPID cervical coil can be angled slightly for kyphotic patients. An angle sponge can be placed under the base of the coil (by the patient’s head) to aid in positioning.

Figure 52 On left, patient positioned in RAPID Cervical coil that has been angled slightly; on right, drawing of connector cover plates and their placement in RAPID cervical coil
CTL Spine Coil

If a patient is to have more than one spine exam performed, and one exam includes the cervical spine, the CTL spine coil is a good choice. The CTL spine coil has 8 channels, as does the smaller RAPID cervical coil. However, the CTL coil’s 8 channels must cover all 4 mode settings for the CTL coil - C, C-T, T and L modes. The CTL coil should be placed directly in the trough of the patient table, with the cervical portion as close as possible to the end of the table nearest to the magnet. Pads are supplied for inside the CTL coil, and additional table pads should be added for patient comfort. The patient should be positioned in the coil with their shoulders in contact with the bridge piers, and the cervical spine in a midline position. The bridge of the coil is then attached to the base of the coil. Sponges and pads should be used to immobilize the patient in the cervical portion of the coil. The transaxial and sagittal laser lights should be centered on the patient’s hyoid bone, which approximates the location of C3.

If only the cervical spine is to be imaged, the lower spine bridge does not need to be attached. For patient safety, connector cover plates must be inserted in the receptacles where the bridge of the coil is normally attached. The cervical portion of the CTL coil can be used without the anterior cervical bridge in place if necessary, although SNR deteriorates by approximately 50%. Protocols have been developed for use of the CTL coil’s cervical portion with no bridge, and are available in the System Directory. Additionally, for patient safety, connector cover plates must be inserted in the receptacles where the bridge of the coil is normally attached.

![Figure 53 On left, patient positioned in CTL coil for cervical spine exam; on right, drawing of connector cover plates and their placement in CTL coil](image)
Solenoid Coil

For patients who cannot be accommodated by the RAPID Cervical coil or the CTL coil, the 1-channel Solenoid coil can be used. Trough and table pads should be placed on the table as necessary for patient comfort. The solenoid coil is placed on top of the pads, between the marking on the patient table and the end of the table nearest the magnetic field. Place the coil as close to a midline position as possible, to minimize centering adjustments once the patient is positioned in the coil. For optimal performance, the solenoid coil should be maintained as close to a perpendicular position to the patient table as possible. The patient’s hyoid bone should be centered with the transaxial laser, and their mid-sagittal plane aligned with the sagittal laser. Protocols have been developed for use of the solenoid coil for a cervical spine exam, and are available in the System Directory.

Figure 54 On left, patient positioned in Solenoid coil with additional padding under their head; on right, patient positioned in Solenoid coil directly on table pads
Echelon OVAL MRI System

The 1.5T Echelon OVAL system incorporates the WIT (Workflow Integrated Technology) RF coils for scanning. The coil of choice for a cervical spine study is the WIT Posterior Head/Neck coil with the WIT Anterior Neck coil attachment. An alternative is the WIT Posterior Head/Neck coil with the WIT Anterior Neurovascular coil attachment. The WIT Posterior Head/Neck coil can be plugged into the patient table at either end, for head-first or feet-first imaging. The Echelon OVAL system incorporates various coil pads and table pads for patient comfort, as well as numerous positioning pads and sponges for patient safety, comfort and immobilization purposes.

Coils and Positioning

- WIT Posterior Head/Neck Coil, WIT Anterior Neck Coil Attachment
- WIT Anterior Neck Coil Attached to WIT Posterior Head/Neck Coil
• WIT Anterior Neurovascular Coil Attachment

WIT Posterior Head/Neck Coil with WIT Anterior Neck Coil Attachment

The WIT Posterior Head/Neck coil can be positioned and plugged in at either the head or foot end of the table for cervical spine imaging. (In this example, it is plugged in at the foot of the table). A head/neck WIT Anterior Neurovascular Coil attachment coil pad is furnished with the coil. The WIT Posterior Spine coils can remain plugged into the table, with the spine coil pad placed on top of them. The large table pad should fit into the spine coil pad at the head end of the table for a comfortable tabletop for the patient. The patient should be positioned in the WIT Posterior Head/Neck coil with their shoulders touching the end posts of the coil. Pads and/or sponges should be inserted between the patient’s head and the coil surface for patient safety and immobilization purposes. The WIT Anterior Neck coil attachment is placed on the WIT Posterior Head/Neck coil, and gently pushed down to engage the latch. The transaxial laser light should be centered to the patient’s hyoid bone, which approximates the position of C3.
WIT Posterior Head/Neck Coil with WIT Anterior NeuroVascular Attachment

The WIT Anterior Neurovascular coil attachment can also be used for cervical spine imaging, or when more anatomical coverage is needed, such as for head and neck vascular studies (e.g., aortic arch through Circle of Willis). This coil attaches to the WIT Posterior Head/Neck coil in the same manner as the WIT Anterior Neck coil attachment—when placed over the WIT Posterior Head/Neck coil, a gentle push is required to engage the latch. The WIT Anterior Neurovascular coil attachment includes a mirror that can be adjusted to the patient's liking for relief of claustrophobia.

Figure 55 WIT Posterior Head/Neck coil pad placed inside coil, with spine coil pad and large table pad in place

Figure 56 WIT Posterior Head/Neck coil with Anterior Neck coil attachment in place on left; Anterior Neurovascular coil attachment in place on right
Echelon MRI System

The coil of choice for a cervical spine on the 1.5T Echelon system is the CTL coil. Additional optional coils that are recommended for cervical spine exams are the Cervical Spine coil, and the Neuro Vascular coil. The Echelon system incorporates various coil pads and table pads for patient comfort, as well as numerous positioning pads and sponges for patient safety, comfort, and immobilization purposes.

Coils and Positioning

- 8- or 10- Channel CTL Coil

- Optional 6- Channel Cervical Coil
• **Optional 8- Channel Neuro Vascular Coil**

### 8- or 10- Channel CTL Coil

The CTL coil is the recommended coil for cervical spine exams. It will have either 8 or 10 channels, which are divided amongst the 4 modes- C, CT, T, and L. The C and/or CT modes are most commonly used for cervical spine imaging. The CTL coil is placed directly in the trough of the table, and can be positioned for either head-first or feet-first scanning. A large pad is supplied with the CTL coil, and additional table pads should be added for patient comfort. The patient should be positioned in the coil with their shoulders in contact with the bridge piers, and their cervical spine in a midline position. The bridge of the coil is then attached to the base of the coil. Sponges and pads should be used to immobilize the patient in the cervical portion of the coil. The transaxial laser light should be centered on the patient’s hyoid bone, which approximates the location of C3.

The cervical portion of the CTL coil can be used without the anterior cervical bridge in place if necessary, although SNR deteriorates by approximately 50%. Protocols have been developed for use of the CTL coil’s cervical portion with no bridge, and are available in the System Directory. Additionally, for patient safety, the attached connector cover plates must be inserted in the receptacles where the bridge of the coil is normally attached.
Optional Cervical Coil

The optional 6-channel Cervical coil provides optimized SNR and signal uniformity necessary for high quality images of the cervical spinal cord, cervical nerve roots, and vasculature of the cervical spine region. The Cervical coil can be placed at either end of the Echelon patient table, so patients can be positioned for head-first or feet-first scanning. The coil base fits into the trough of the table, enabling isocenter positioning. The patient should be positioned in the coil with their shoulders in contact with the bridge piers, and their cervical spine in a midline position. The bridge of the coil is then attached to the base of the coil. Sponges and pads should be used to immobilize the patient in the cervical coil. The transaxial laser lights should be centered on the patient’s hyoid bone, which approximates the location of C3-C4. Centering of the laser light should be performed to the patient’s anatomy, rather than to the centering marks on the bridge of the coil.

Figure 58 Patient positioned in optional Cervical coil
Optional Neuro Vascular Coil

The optional 8-channel Neuro Vascular coil provides the flexibility needed to image cranio-cervical anatomy. Multiple coil applications, including head, cervical, and head/neck, minimize patient re-positioning. The Neuro Vascular coil can be placed at either end of the Echelon patient table, so patients can be positioned for head-first or feet-first scanning. The coil base fits into the trough of the patient table, enabling isocenter positioning. The coil is fitted with a pad, and additional table pads should be placed on the table for patient comfort. Once the patient is positioned in the coil, the anterior portion of the coil should be fitted to the coil base, and securely latched using the blue handle. The upper portion of this coil also includes a mirror that can be adjusted to the patient’s liking for relief of claustrophobia.

Figure 59 Patient positioned in optional Neurovascular coil
Scan Setups

The following are HHA suggestions for cervical spine imaging. Always check with your radiologist for his/her imaging preferences. A three-plane scanogram should be performed at the beginning of this protocol. Coronal scans are not generally part of a cervical spine protocol.

Sagittal Scans

Sagittal slices should be planned on coronal and axial plane images. On the coronal plane images, slices should be angled parallel to the spinal cord. On the axial plane images, slices should be angled to be parallel to a line running along the center of the vertebral body through the length of the spinous process. Coverage should include above C1 to approximately the level of T4, depending on radiologist’s preferences. The sagittal slices should cover the spine from the lateral border of the right transverse process to the lateral border of the left transverse process. A saturation band should be positioned over the esophagus to reduce artifacts from swallowing.

![Sagittal slice setup using coronal and axial images](image-url)
Axial Scans

Axial slices should be planned on sagittal and coronal plane images. On the sagittal plane images, slices should be angled so they are perpendicular to the spinal cord. On the coronal plane images, slices should be angled so they are parallel to the intervertebral disc spaces. Coverage should include from C2 to T1, depending on radiologist’s preferences. A saturation band may be included and placed anteriorly to the esophagus. It was not included in this example, as a T1-weighted axial sequence was planned.

Figure 61 Axial slice setup using sagittal and coronal images
MRA of Carotids

2D TOF

2D TOF is commonly used for imaging of long vascular segments that run perpendicular to the plane of imaging (such as femoral and carotid arteries). Multiple thin slices are obtained as a stack in a plane perpendicular to the course of the imaged blood vessels. TR values are kept short to suppress background tissues and accentuate flow-related enhancement. The slices are acquired sequentially; the Hitachi sequence demonstrated below included an overlap, in which case the Interval parameter is less than the Thickness parameter. A “walking” saturation band is placed on the upstream side of each slice to suppress contaminating signal from venous inflow. Slices are typically centered in the C3-C4 area, approximating the carotid bifurcation. The 2D method offers reasonable imaging times with excellent sensitivity to slow flow. Imaging of long vascular segments is possible by increasing the number of slices. Disadvantages of 2D imaging include insensitivity to in-plane flow, and patient motion artifacts that may create misregistration.

Figure 62 2D TOF slice setup with "walking" saturation band positioned superior to slices
**3D TOF**

The 3D TOF mode is used where the imaged anatomy encompasses a relatively small area, and vessels have various flow directions (e.g., the carotid bifurcation or circle of Willis). 3D methods offer high spatial resolution and high signal-to-noise. Nearly isotropic (square) voxels may be obtained, allowing multiplanar reconstruction. A “walking” saturation band is placed on the upstream side of each slice to suppress contaminating signal from venous inflow. Slices are typically centered in the C3-C4 area, approximating the carotid bifurcation. Disadvantages of 3D TOF MRA include relative insensitivity to slow flow and saturation effects that limit maximum slab thickness of each acquisition. Imaging times are also longer than 2D TOF techniques. Although motion artifacts affect only single slices in 2D TOF MRA, all slices are affected in 3D acquisitions, which could possibly render the study uninterpretable.

![Figure 63 Graphic that demonstrates differences between 2D and 3D TOF acquisitions](image)

![Figure 64 3D TOF slab setup with "walking" saturation band positioned superior to slabs](image)
Conclusion

This concludes the Cervical Spine module. You must complete the post-test for this activity with a score of 75% or better in order to receive Continuing Education credits.
Appendix A: References for Cervical Spine Imaging Module

- Bickle, Dr. Ian, and Wein, Dr. Sara et al. (n.d.). *Spinal ependymoma*. Retrieved from [https://radiopaedia.org/articles/spinal-ependymoma](https://radiopaedia.org/articles/spinal-ependymoma)
- Hacking, Dr. Craig, and Yap, Dr. Ki et al. (n.d.). *Multiple myeloma*. Retrieved from [https://radiopaedia.org/articles/multiple-myeloma-1](https://radiopaedia.org/articles/multiple-myeloma-1)
• Knipe, Dr. Henry, and Weerakkody, Dr. Yuranga et al. (n.d.). Congenital cervical teratoma. Retrieved from https://radiopaedia.org/articles/congenital-cervical-teratoma
• Luijkx, Dr. Tim, and Radswiki et al. (n.d.). Diffuse idiopathic skeletal hyperostosis. Retrieved from https://radiopaedia.org/articles/diffuse-idiopathic-skeletal-hyperostosis
• Murphey, Mark D., Choi2, James J., Kransdorf, Mark J., Flemming, Donald J., Gannon, Frances H. (Published Online 1September2000). Imaging of Osteochondroma: Variants and Complications with Radiologic-Pathologic Correlation. Retrieved from https://pubs.rsna.org/doi/full/10.1148/radiographics.20.5.g00se171407
• Samartzis, Dino, Gillis, Christopher C., Shih, Patrick, O’Toole, John E., Fessler, Richard G. (Published Online 31March2015). Intramedullary Spinal Cord Tumors: Part I-Epidemiology, Pathophysiology, and Diagnosis. Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4577312/
• St-Amant, Dr. Maxime, and Dixon, Dr. Andrew et al. (n.d.). *Haemosiderin cap sign*. Retrieved from https://radiopaedia.org/articles/haemosiderin-cap-sign
• Wein, Dr. Sara et al. (n.d.). *Spinal neurofibroma*. Retrieved from https://radiopaedia.org/articles/spinal-neurofibroma
Appendix B: References for Pictures for Cervical Spine Imaging Module

- Figure 1 – [http://anatomycorner.com/main/image-gallery/bones/](http://anatomycorner.com/main/image-gallery/bones/)
- Figure 2 – [https://mrimaster.com/anatomy%20spine%20c%20spine%20axial.html](https://mrimaster.com/anatomy%20spine%20c%20spine%20axial.html)
- Figure 3 – [https://mrimaster.com/anatomy%20spine%20c%20spine%20sagittal.html](https://mrimaster.com/anatomy%20spine%20c%20spine%20sagittal.html)
- Figure 4 – [https://mrimaster.com/anatomy%20neck%20arteries.html](https://mrimaster.com/anatomy%20neck%20arteries.html)
- Figure 5 – [https://mrimaster.com/anatomy%20spine%20c%20spine%20sagittal.html](https://mrimaster.com/anatomy%20spine%20c%20spine%20sagittal.html)
- Figure 6 – [https://mrimaster.com/anatomy%20brachial%20plexus%20coronal.html](https://mrimaster.com/anatomy%20brachial%20plexus%20coronal.html)
- Figure 8 – [http://www.svuhradiology.ie/case-study/cervical-myelopathy-mri/](http://www.svuhradiology.ie/case-study/cervical-myelopathy-mri/)
- Figure 9 – [https://commons.wikimedia.org/wiki/File:Cervical_Spine_MRI_showing_degenerative_changes.jpg](https://commons.wikimedia.org/wiki/File:Cervical_Spine_MRI_showing_degenerative_changes.jpg)
- Figure 27 – [https://www.orthopaedicsone.com/display/PORT/Alveolar+Soft+Part+Sarcoma](https://www.orthopaedicsone.com/display/PORT/Alveolar+Soft+Part+Sarcoma)
- Figure 28 – [https://radiopaedia.org/cases/ganglioneurocytoma](https://radiopaedia.org/cases/ganglioneurocytoma)
- Figure 29 – [https://radiopaedia.org/cases/osteochondroma-of-the-cervical-spine](https://radiopaedia.org/cases/osteochondroma-of-the-cervical-spine)
- Figure 30 – [https://radiopaedia.org/cases/multiple-myeloma-cervical-spine](https://radiopaedia.org/cases/multiple-myeloma-cervical-spine)
- Figure 33 – [https://radiopaedia.org/cases/spinal-schwannoma-cervical](https://radiopaedia.org/cases/spinal-schwannoma-cervical)
- Figure 34 – [https://radiopaedia.org/cases/spinal-meningioma-at-the-upper-cervical-level](https://radiopaedia.org/cases/spinal-meningioma-at-the-upper-cervical-level)
- Figure 35 – [https://radiopaedia.org/cases/spinal-ependymoma](https://radiopaedia.org/cases/spinal-ependymoma) for image on left; [https://radiopaedia.org/cases/ependymoma-cervical-cord](https://radiopaedia.org/cases/ependymoma-cervical-cord) for image on right
- Figure 36 – [https://radiopaedia.org/cases/ganglioglioma-of-the-cervical-cord](https://radiopaedia.org/cases/ganglioglioma-of-the-cervical-cord)
- Figures 37, 38 – [https://radiopaedia.org/cases/haemangioblastoma-cervical-cord](https://radiopaedia.org/cases/haemangioblastoma-cervical-cord)
- Figure 39 – [https://radiopaedia.org/cases/von-hippel-lindau-1](https://radiopaedia.org/cases/von-hippel-lindau-1)
- Figure 40 – [https://emedicine.medscape.com/article/345105-overview#a4](https://emedicine.medscape.com/article/345105-overview#a4)
- Figures 43, 44 – [https://www.nature.com/articles/scsandc20156/figures/1](https://www.nature.com/articles/scsandc20156/figures/1)
- Figures 47-49 – [https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3463148/](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3463148/)
- Figure 50 – [https://radiopaedia.org/cases/diffuse-idiopathic-skeletal-hyperostosis-dish-2](https://radiopaedia.org/cases/diffuse-idiopathic-skeletal-hyperostosis-dish-2)
- Figures 51-62, 64 – Courtesy of Hitachi Healthcare Americas
- Figure 63 – [http://mri-q.com/2d-vs-3d-mra.html](http://mri-q.com/2d-vs-3d-mra.html)