New developments in neurosurgery

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Imaging

Advanced imaging techniques like computed tomography (CT) and magnetic resonance imaging (MRI) have changed the landscape for the veterinary neurosurgeon dramatically. CT and MRI scanners are now more commonly available in veterinary practice.
With modern fast helical (64-, 128-) multi-slice CT scanners, imaging of tissue objects with 1 or 2 mm slices is fast (usually less than 30 minutes) and gives a wealth of data. Data storage, data reconstruction and interpretation of hundreds to thousands of slices within a short time span requires specialized knowledge and experience. CT is excellent for bone structures but also for soft tissue (when contrast medium is given) and air-filled cavities. MRI is excellent for (water-rich) soft tissue structures (like brain and spinal cord), but not good for air-filled spaces (like lungs). Likewise, MRI is not the best imaging tool for bone structures but recent research is focusing on MRI bone sequences and experimental versions have already reached the same quality as CT, so ongoing developments may shift the paradigm -CT for bone and MRI for soft tissue-. With respect to MRI and the veterinary field another important issue arises and that is the difference between low field (0.3 Tesla or less) and high field (1.0 to 3.0 Tesla) MRI scanners. In general, low field scanners produce images with low resolution at slow speed. High field scanners produce higher resolution images at a faster speed. The resolution of an image also depends on the size of the tissue object that is scanned. Therefore the quality of images that are produced by low field scanners of small animals like cats and small dogs (<10 kg) may not be sufficient to show detailed pathology in e.g. brain or spinal cord in comparison with high field scanners. This knowledge should be used responsibly by radiologists and managers of low field scanners when cats or small dogs are referred for MRI to prevent re-scanning at other institutions with high field scanners (with unnecessary anesthetic burden for the patient and financial burden for the owner).

The true value of CT and MRI for the neurosurgeon lies in the reconstructions in sagittal and axial planes, or multiplanar reconstructions (MPR) allowing to scroll through tissue objects from all angles. For bone structures like spine and skull, 3D reconstructions allow the surgeon to look at the pathology from all angles, and to prepare the surgical approach *in silico*, and with software tools like 'knife', even to practice surgical excisions *in silico*. The surgeon should not be limited by expensive software licences for Picture Archiving and Communication System (PACS) systems. The medical field has realized this for a long time and therefore freeware software tools are available on the web that allow the surgeon to download software tools at no or very low cost and work with DICOM® (Digital Imaging and Communications in Medicine). DICOM is the international standard to transmit, store, retrieve, print, process, and display medical imaging information. DICOM makes medical imaging information interoperable, integrates image-acquisition devices, PACS, workstations, and printers from different manufacturers, is actively developed and maintained to meet the evolving technologies and needs of medical imaging, and is free to download and use. There are many free DICOM viewers available on the internet but common viewers that are used by radiologists, neurologists and neurosurgeons are:

RadiAnt® (https://www.radiantviewer.com): Windows based dicom viewer.
OsiriX® (https://www.osirix-viewer.com): Apple based dicom viewer.
The Horos Project® (https://horosproject.org): Apple based dicom viewer.
Horos and OsiriX are the top two medical image viewers for Apple computers. However, the two products have different functionalities and work very differently in many respects. To read more in the differences between Horos and OsiriX , please see:https://www.purview.net/blog/horos-v.-osirix-whats-the-difference

Neurosurgical indications

The most common neurosurgical indications of the cranium are neoplasia (meningioma and glioma), trauma (skull fracture, bite wounds), hydrocephalus, and brain abscess.
The most common neurosurgical indications of the spine have been degenerative disorders like disc herniation (cervical and thoracolumbar disc herniation, caudal cervical spondylomyelopathy, degenerative lumbosacral stenosis), spinal neoplasia, spinal trauma (fracture and luxation) and infection (discospondylitis). Due to the availability of advanced imaging modalities like CT and MRI in veterinary practice and further veterinary specialization, more and more CT and MRI are performed in dogs and cats with neurological signs. This has resulted in more frequent diagnosis of anomalies and the question then arises whether these can be treated surgically. Two new groups of disorders are more frequently seen and have become part of the list of neurosurgical indications, i.e., spinal cyst and spinal deformity.

Spinal cysts are classified as extradural or intradural cysts.
Extradural cysts (of non-meningeal origin) are recognized in three types: (1) synovial cysts containing a lining of synovia-like epithelial cells, (2) ganglion cysts, originating from vertebral ligaments, consisting of a collagenous capsule surrounding myxoid material and (3) discoid cysts originating from the annulus fibrosus containing degenerative fibrous material without a synovial lining. Extradural synovial cysts have been referred to as intraspinal synovial cysts, juxtafacet cysts, and ganglion cysts. These cysts originate from the zygapophyseal joint (**Figure 1**) of the vertebral articulations and are located extradurally. Histologically, the cysts can be divided into synovial cysts, which are those that have a synovium-like lining of epithelial cells, and ganglion cysts, which do not have this lining and are thought to result from mucinous degeneration of the articular cartilage. Discoid cysts (**Figure 2**) have been later identified as true herniations of the nucleus pulposus and are now called hydrated nucleus pulposus extrusion (HNPE). They are marked by extrusion of hydrated NP material that reveals itself on T2-weighed MRI as hyperintense (cyst-like) masses compressing the spinal cord. They usually occur in the caudal cervical region and lead to acute severe tetraparesis or tetraplegia. However, they carry a favourable prognosis with conservative and surgical management. In the lumbosacral area, discoid cysts can also remain within the contours of the bulging disc and represent extrusion of NP material within the dorsal annulus fibrosis and are referred to on T2W-imaging as hyperintensity zones (HIZ).
Intradural cysts (**Figure 3 and 4**) arise from the meninges and contain cerebrospinal fluid (CSF). These include arachnoid cysts that lack epithelial lining. For this reason they are not true cysts and the term spinal arachnoid diverticula (SAD) is more appropriate. Subarachnoid diverticula are defined as focal accumulations of cerebrospinal fluid within the arachnoid membrane or subarachnoid space. This fluid-filled area tends to form over the dorsal (Figure 4) or dorsolateral aspect of the spinal cord, with very few reports of ventral diverticula. The structures have no epithelial lining; therefore, technically, they are not a true cyst and instead have been referred to as a "pseudocysts." Pseudonyms for this condition include arachnoid pseudocyst, meningeal or leptomeningeal cyst, and arachnoid cyst. The pathogenesis of this condition has not been elucidated, but malformation of the arachnoid space may occur in some animals during embryogenesis, or acquired malformation may occur secondary to trauma, inflammation, neoplasia, or ischemia later in life. The condition is most commonly congenital in origin, but it may occur secondary to a concurrent spinal cord disorder. Accumulated cerebrospinal fluid is speculated to cause compression of the adjacent spinal cord, resulting in clinical signs. Commonly affected sites include the cranial cervical and caudal thoracic spinal cord regions. Clinical features include a protracted progressive history of general proprioceptive ataxia and upper motor neuron paresis and also incontinence. Any breed or age can be affected, but younger adult (<18 months) Pugs and Rottweilers represent the most commonly reported breeds, and males tend to be predisposed.

A presumptive diagnosis of extradural or intradural synovial cysts can be achieved via imaging, with MRI being the imaging modality of choice. In human beings, MRI is reported to have a sensitivity of 90% for the diagnosis of extradural synovial cysts, compared with 70% with CT. MRI in dogs reveals the extradural cysts as well-circumscribed extradural mass(es) on one or both sides of the vertebral foramen. Extradural synovial cysts seen on MRI are hyperintense in T2-weighted images, with hypointensity, isointensity, or hyperintensity in T1-weighted images, depending on whether the content of the cyst is mostly synovial fluid or mucinous or haemorrhagic material. Mild to moderate contrast enhancement surrounding the cyst is commonly observed on T1-weighted images acquired after intravenous contrast injection. In case of intradural cysts, the cysts reveal themselves as well-circumscribed intradural masses within the contours of the spinal cord, round to oval in case of cysts, or elongated and usually with a peripheral location in case of diverticula.
The surgical technique for treatment of spinal cysts depends on the location of the cyst. Dorsal laminectomies are indicated for cysts in the cervical and thoracic vertebral column and at the lumbosacral articulation; dorsal laminectomies and/or hemilaminectomies are often used for cysts in the thoracolumbar vertebral column.
In the case of extradural cysts, the entire cyst and periarticular soft tissues should be removed to minimize the possibility of recurrence. If decompression of the vertebral segment results in instability, or if instability is thought to be present, stabilization is recommended.
In the case of intradural cysts the surgical approach also depends on the location of the cyst in the spine and is similar to extradural cysts. Usually a dorsal laminectomy is chosen for the cervical, thoracic spine, and lumbosacral articulation (**Figure 5 and 6**), and for the thoracolumbar spine and dorsal laminectomy and/or hemilaminectomy. However, once the location has been exposed removal of the cysts depends on the presentation and location of the cyst in relation to the spinal cord or cauda equina. When the cyst is largely extradural, it can be carefully detached from the meninges using fine neurosurgical probes, ophthalmological scissors and resected. The dura may be opened in this process and can be closed using polydiaxone 5-0 or 6-0 interrupted sutures. In case the cyst is located intradural, first the spinal cord is inspected carefully using magnification. Many times the surgeon is able to see a region of dark discoloration of the spinal cord due to the fluid-filled cavity (cyst) with the overlying dura mater. This observation directs the surgeon where to make the dural incision. The dura overlying the cyst is opened using a durotomy with no. scalpel or arachnoid beaver knife. The dural incision can also be started with the sharp point of a 18G needle that is used as a knife. Once an opening has been created, CSF of cyst content will come out which is easily identified under magnification. The dural opening can then be further opened using the knife. Following the durotomy the interior is inspected and the surgeon has to determine whether the spinal cyst is still intact (visualization of intact cyst wall within the dura mater) or whether the cyst cavity or diverticulum has been opened. When the cyst wall is still intact, the cyst surroundings are carefully explored without disturbing the spinal cord parenchyma and the cyst is retracted through the dural opening and sent in for histological examination (**Figure 6**). When a complete cyst with an intact cyst wall has been removed it can be decided to close the dura mater with interrupted polydiaxone 5-0 or 6-0 sutures. In case durotomy also leads to opening of the cyst and collapse of the cyst, the surgeon may attempt to remove remnant cyst wall for histological confirmation of the cyst type. In case a diverticula was opened it is usually not possible to remove cyst wall of capsule. In that case a small 1x5 mm strip of the dura may be removed for histological examination. In the case of opening an intradural cyst or diverticulum without a clear cyst wall, the dura is usually left open to allow further drainage of CSF or cyst contents. A small piece of clean fat (harvested from the subcutis) can be left inside the opening to delay closure. Another option in larger dural openings is marsupialization where the dura mater is sutured to fascial tissue surrounding the laminectomy slot.

Spinal deformity, like scoliosis, is common in humans but rare in dogs. In humans the most common spinal deformity in the right S-bended idiopathic scoliosis of thoracic and lumbar spine in young individuals that worsens as the person becomes adult. The condition has devastating psychological and physical consequences and greatly affects quality of life. Multiple traumatic invasive surgeries are needed to correct the spinal deformity and the state-of-the art surgical technique is angular correction and fixation with pedicle screws and bilateral rods placed on the dorsal (posterior) side of the spine.
Spinal deformity like scoliosis is extremely rare in dogs and there are only few case reports. In recent years another spinal deformity has been reported in young pugs and French Bulldogs, and more recently also in Shepherd dogs with an age less than 1 year that cause severe clinical signs and neurological deficits. The condition is marked by a severe mid-thoracic kyphosis which is only apparent on imaging but usually not on outward inspection of the dog. The condition is most likely congenital and hereditary, although no causative genes have been identified yet. Dogs slowly develop paraparesis and paraparalysis during growth in the first year of life and this is the reason that owners will consult a veterinarian. The condition is progressive, in the beginning dogs are ataxic and paretic in the pelvic limbs which may evolve in full grade 4 paraparalysis and urinary incontinence and ultimately in grade 5 paraparalysis without deep nociception. Surprisingly the dogs do not show significant spinal pain during the course of the disease, most likely due to the gradual development of the spinal deformity.
The neurological localisation is typical T3-L3, only the pelvic limbs are affected and not the forelimbs. Proprioception and postural reactions in the pelvic limbs are decreased or absent, spinal reflexes in the pelvic limbs are present or show hyperreflexia by loss of central inhibition. Deep pain nociception is normal but in grade 5 it is absent. Diagnosis is confirmed by imaging. Radiography (**Figure 7**) usually shows abnormal vertebral anatomy in the mid-thoracic region like hemivertebrae, block vertebrae or butterfly-wing shaped vertebrae. In the region with the abnormal vertebrae a severe kyphosis develops with an angulation that may approach 90 degrees. On MRI (**Figure 8**) and CT reconstructions in the sagittal plane, the effect on the spinal cord becomes apparent: at the site of maximum angulation, the spinal cord is flattened and pinched off and this explains the dramatic development of the neurological deficits.

Conservative treatment with nonsteroidal anti-inflammatory drugs or steroids may result in temporary improvement of the neurological deficits. As soon as the diagnosis has been confirmed by imaging, the only effective treatment for a functional prognosis in the long term is surgical correction of the angular deformation. This is a huge challenge since 1) the developing spine has an inherent pathological growth disorder, 2) the bone consists of vertebral bodies with cancellous bone (and thus limited holding power), and 3) the dogs are still young animals. The surgery usually consists of a uni- or bilateral right mid-thoracic approach to the spine, resection of the rib-vertebra junctions, opening of the thoracic cavity, partial or total corpectomy of the abnormal vertebral body or the affected endplate-disc-endplate unit, or 360° complete excision of the abnormal vertebra at the site of the maximum angulation, followed by angular correction of the spine (around 30 to 50° correction is sufficient to decompress the spinal cord) and spinal fixation with implants.

Spinal implants that have been used are: screws or pins with methylmethacrylate (PMMA), clamp-rod internal fixation (CRIF), string-of-pearl (SOP) plate with locking screws, reconstruction plates and screws, titanium Unilock locking plates with locking screws, and pedicle screw-rod fixation (PSRF). The plate / bar / rod construct should allow bending in three dimensions, to follow the curvature of the abnormal spine, and preferably re-adjustment should be possible during surgery (not possible with PMMA) when making the angular correction. For that reason CRIF, SOP, titanium locking plates, and PSFR are preferred. Surgery is invasive and may result in significant blood loss. Anaesthetic considerations should be taken into account: young animal, open thorax, restoration of negative pressure upon closing the thorax, blood transfusion or plasma expanders, arterial pressure monitoring, monitoring cardiac (ECG) and respiratory function (capnography, oxygen pulsoximetry) and adequate analgesia. Postoperative recovery is preferably on an intensive care unit and rehabilitation with animal physiotherapy and hydrotherapy is recommended. Prognosis of this condition without surgical intervention is guarded.

New spinal implants, intervertebral spacers, and additive manufacturing (3D printing)

Intervertebral spacers are emerging as new implants that are used in caudal cervical spondylomyelopathy and degenerative lumbosacral stenosis.

Caudal cervical spondylomyelopathy: Ventral decompression ('ventral slot') is indicated in static ventral compressive spinal cord lesions but these are rare in the true wobbler dog. Ventral distraction and stabilization is indicated in one or multiple dynamic ventral compressive spinal cord lesion(s), e.g. cervical instability, type II disc degeneration, and dorsal longitudinal ligamentous hypertrophy. Linear distraction of cervical vertebral bodies results in decompression at the site of the dynamic lesion and (temporary) fixation of the vertebral bodies allows fusion to take place which is promoted by cancellous or corticocancellous bone grafts harvested from the proximal humerus. Surgical techniques that have been performed in the past decade are: distraction with a cylindrical cortical allograft kept in place with a plastic Lubra plate, distraction with Steinmann pins or screws and fixation with a polymethyl methacrylate (PMMA) bridge, Harrington rod distraction device, screw and washer technique, and the modified distraction-stabilization technique using an interbody PMMA plug. Fusion or arthrodesis of the cervical vertebrae is promoted by packing cancellous bone around the affected cervical junction. Fusion of cervical vertebrae by the surgical techniques listed is usually by ventral spondylosis as interbody fusion is obstructed by metal implants or PMMA plugs. Complete surgical arthrodesis by spondylosis of the cervical vertebrae was observed only with the screw and washer technique. With long term follow up, the radiographic complications that were seen with screw and washer were migration of the washer in the endplates (so-called subsidence) and adjacent segment disease. The ideal spinal fusion would be direct continuous bone bridging at the level of the vertebral bodies and techniques to stimulate this are now reported or under development. Cervical locking plates and interbody titanium cages like SynCage (DePuy Synthes, Amersfoort, The Netherlands) (**Figure 9**) will probably offer a better way to treat cervical instability and promote fusion than the techniques reported in earlier days. Recently, spinal cages have entered the veterinary field of spinal surgery. The titanium C-LOX cage is available in various sizes and these cages are fixated with 4 titanium screws. The cage can be filled with cancellous bone, a bone substitute, or BMP-2. However, the paradox between a highly flexible cervical spine and rigid implants remains a tension field.

Degenerative lumbosacral stenosis: Dorsal laminectomy is indicated for cauda equina compression without foraminal stenosis or lumbosacral instability. Stabilization by fixation and fusion is indicated when ventral subluxation of S1 is present or in severely deranged lumbosacral junctions (like chronic discospondylitis), or to prevent further development of lumbosacral instability. In addition to fixation, the vertebral junction may need to be distracted with an intervertebral spaces to enlarge to lumbosacral foramina and treat foraminal stenosis and to allow for spinal fusion to take place to replace the stability that is provided by spinal implants on which cannot be relied for the remainder of the dog's life. Pedicle screw-rod fixation has proven to be an adequate stabilization technique in large breed dogs and the ultimate goal of this technique is spinal fusion. Specialized medical devices are generally manufactured for human use, expensive and are not widely used in veterinary surgery for this reason. Other veterinarians have used specialized medical devices like pedicle screw-rod fixation using the USS Small Stature System (DePuy Synthes, Amersfoort, The Netherlands) or the 'string of pearls' (SOP, Orthomed, Huddersfield, UK) locking plate for dorsal fixation/fusion by placing implants into the pedicle of L7. Pedicle screw fixation avoids loading the articular processes, thus allowing more aggressive laminectomy/dorso-medial foraminotomy, and decreased concern over weakening of the articular processes. Screw failure may occur when using SOP implants at the LS junction in dogs over 25kg.

In the last 5 years, vertebral implants are being developed for the veterinary market on a small scale like the Canine Vertebral Screw and Rod Fixation System (Orthopeasia, Bangkok, Thailand) and the Arcas Polyaxial pedicle screws & rods (Artemedics, Minneapolis, MN, USA). Recently, a novel spinal implant system has been described for LS fixation in dogs. The procedure is similar to posterior fixation procedures used in human neurosurgery where fixation screws are connected via polyaxial clamps to rigid rods (Fitzateur, Fitz-Bionics, UK). The Fitzateur implants are too large to be inserted into the pedicle of L7 therefore are angled to engage the vertebral body.

Spinal fusion can be stimulated by the use of interbody cages, e.g. made from titanium or polyether ether ketone (PEEK), that are filled with cancellous bone or BMP-2. Cancellous bone can easily be harvested during the dorsal laminectomy procedure from the spinous processes that are removed or the burring bone debris that is produced when removing the laminar bone. The utility of pedicle screw-rod fixation alone or together with intervertebral spacers like SynCage (DePuy Synthes) or patient-specific 3D-printed titanium implants are under investigation.

PEEK possesses excellent mechanical properties similar to those of human bone due to its Young's modulus that closely resembles that of bone. PEEK is considered the best alternative material other than titanium, which has a Young's modulus different from bone, for orthopedic spine and trauma implants. However, the deficient osteogenic properties and the bio-inertness of PEEK in comparison to titanium limits its field of application. Titanium has a wider application in orthopedic and spine surgery due to its light weight in relation to strength, ease of manufacturing, additive manufacturing properties, bactericidal activity, and osteoconductive and osteo-inductive properties.

Additive manufacturing (3D printing). Due to the availability of fast multi-slice CT scanners and detailed 3D reconstructions, the possibility arises to export the DICOM images to software programs that can segment the 3D reconstructed objects and fabricate replacements after surgical resection *in silico* guided by the medical professional. When the medical professional and the designer have reached consensus on the prototype that needs to replace the disease bone, the file is sent to an industrial laser printer and the replacement is metal printed e.g.in titanium by additive manufacturing. This also allows to print bone specimens (skull, spine, or long bone) in plastic specific for the patient on which the surgical procedure can be performed with a prototype for practicing and refining the surgical technique. Also personalized surgical saw guides can be printed helping the surgeon to precisely perform the marginal excisions. Personalized (patient-specific) saw guides and printed titanium implants can then be sterilized for the actual *in vivo* surgical procedure. The indications for this technique include skull, mandibula, maxilla, dental, spine and long bone procedures. For example, this technique allows 1) printing of skull defects after surgical resection of brain tumor or skull bone tumors after extensive craniectomy, 2) print and restore maxilla and mandibular defects, 3) print intervertebral cages, or 4) print complete vertebral bodies after vertebrectomy.

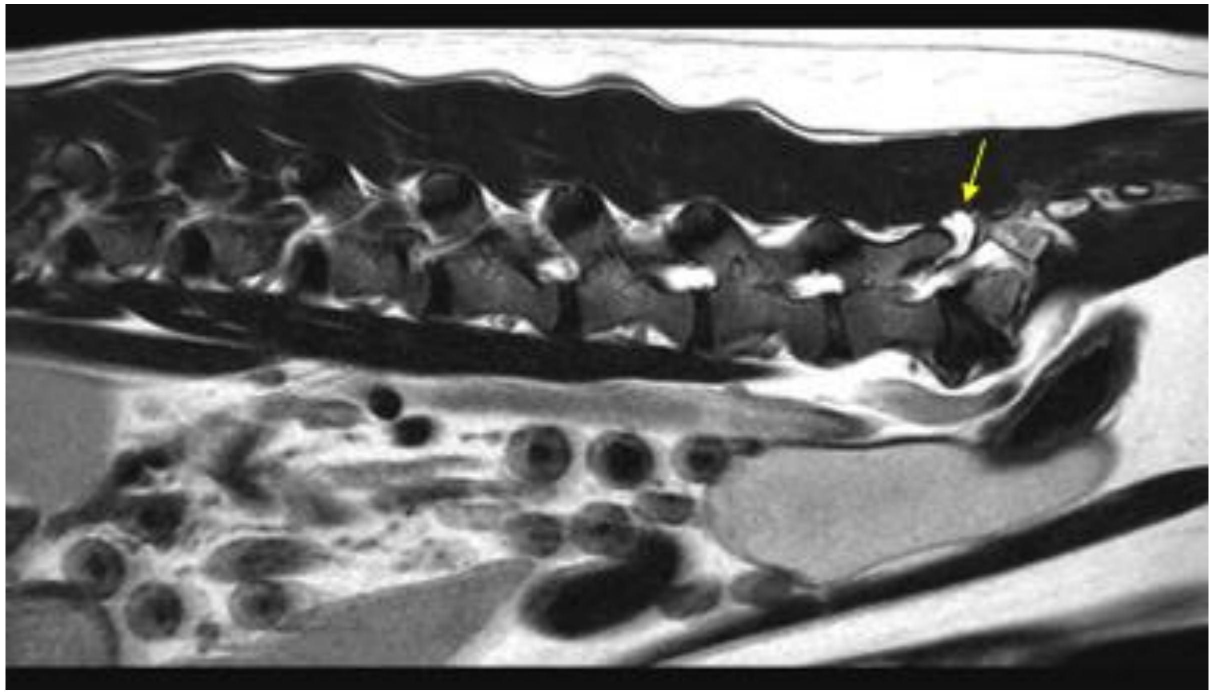


Figure 1. T2W MRI of a 4-year-old Dogo Argentino with low back pain showed degenerative lumbosacral stenosis and a synovial cyst (arrow) originating from the zygapophyseal joint between L7 and S1.

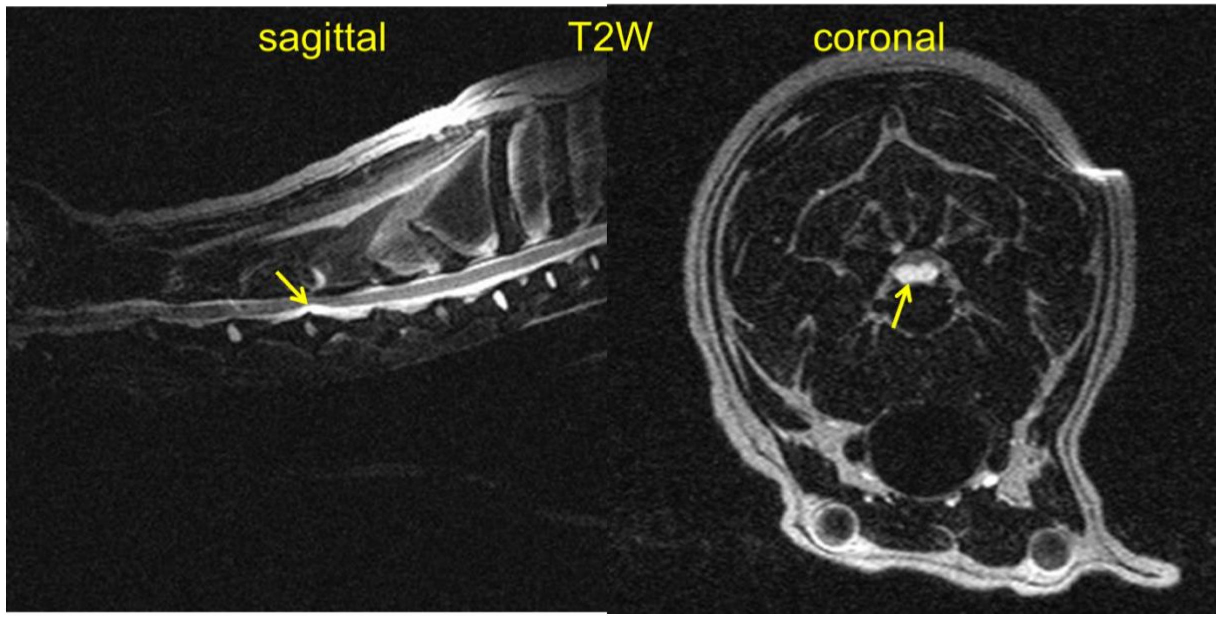


Figure 2. T2W sagittal (left) and transverse (right) MRI showing a hyperintense region (arrow) compressing the spinal cord at C4-C5 in a dog that was presented with acute tetraparalysis. This lesion has been erroneously called a discoid cyst but later research proved that this is a hydrated nucleus pulposis extrusion. The dog underwent ventral decompression and the NP material was removed. The dog showed a rapid full neurological recovery in 2 weeks.

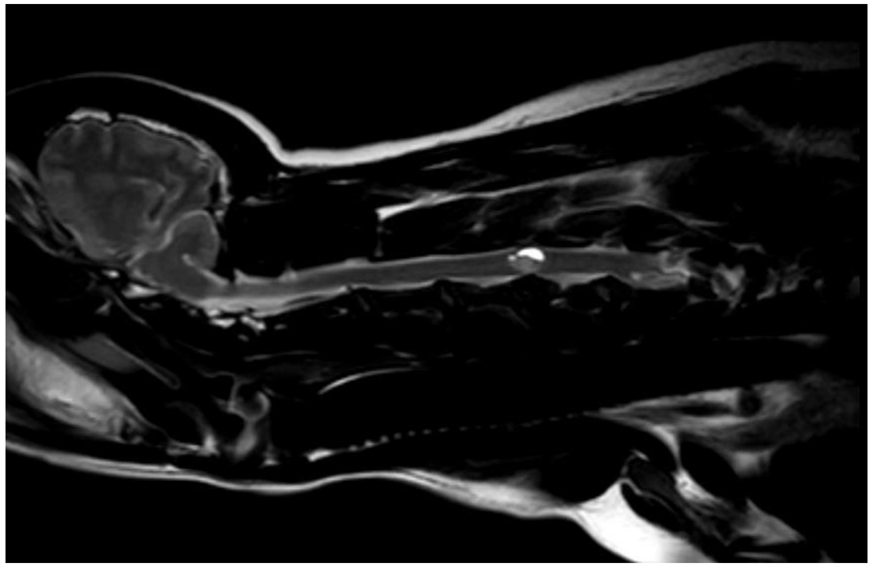
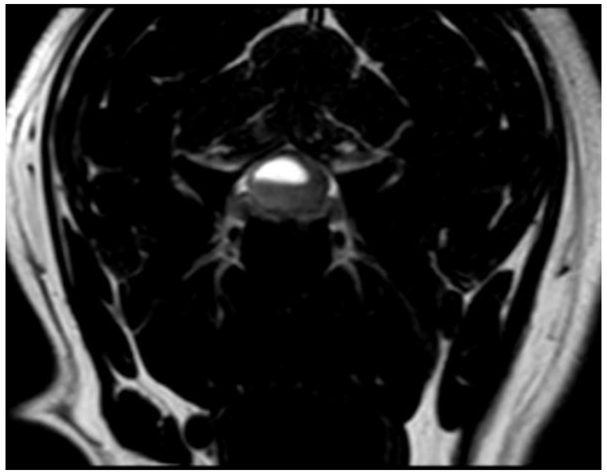


Figure 3. Intradural cystic mass lesion at C4-C5 in a 2-year-old English Cocker Spaniel presented with hemiparesis. The dog was operated by dorsal laminectomy and the spinal cyst was excavated. The dog showed full neurological recovery.



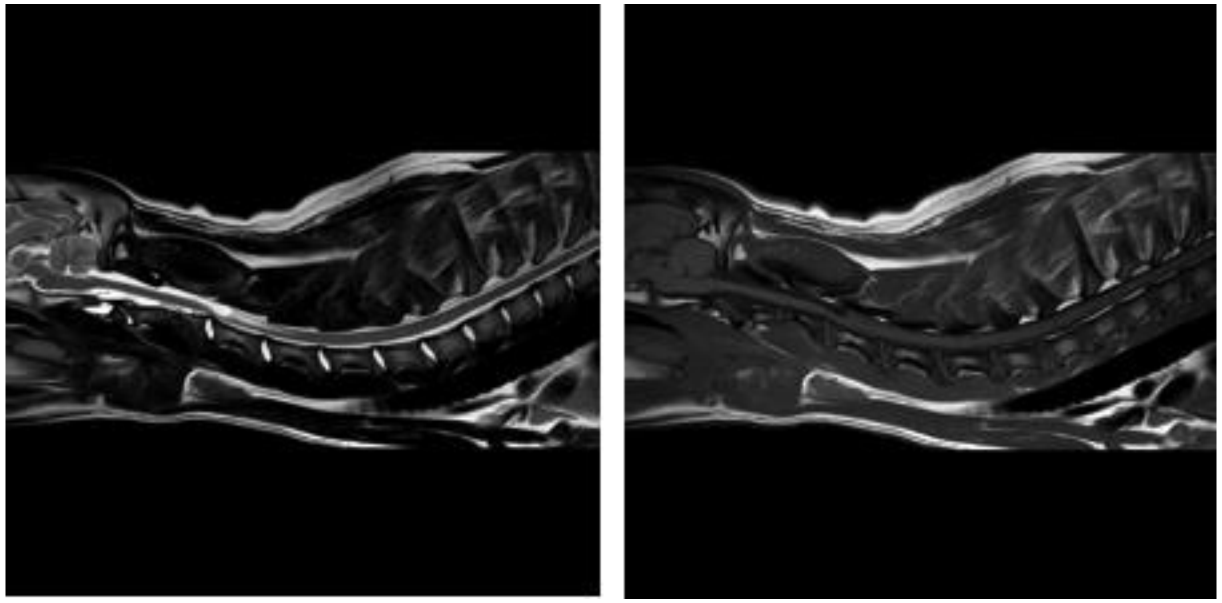


Figure 4 Sagittal T2W (left) and T1W (right) MR image of an intradural subarachnoid diverticula at C2-C3 in a 3-year-old Rottweiler with ataxia.

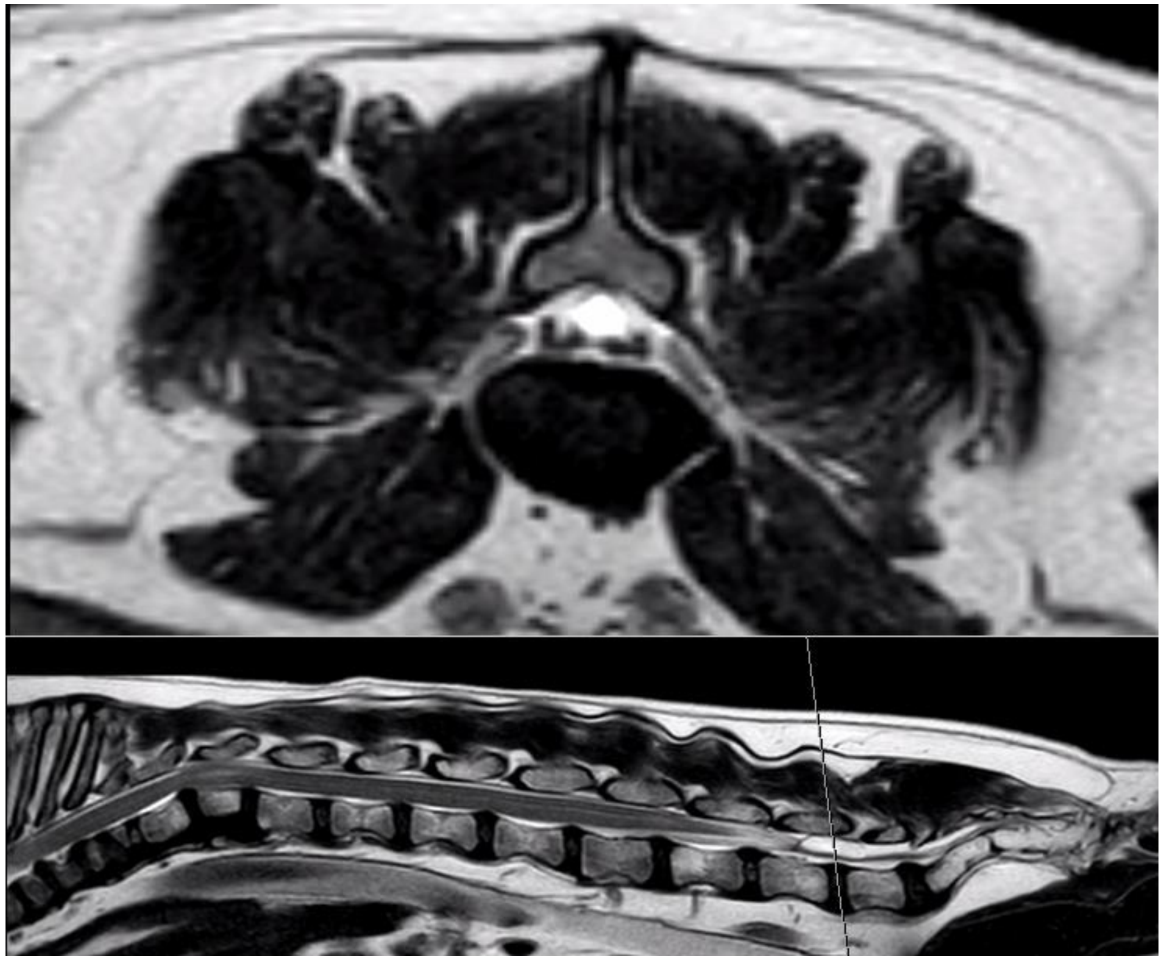


Figure 5. T2-weighted MRI of a dog with an intradural arachnoid cyst in the caudal lumbar (L6-L7) region. The transverse section (top) of the oval cystic lesion depicted on the sagittal scan (bottom) reveals the hyperintense cystic content.

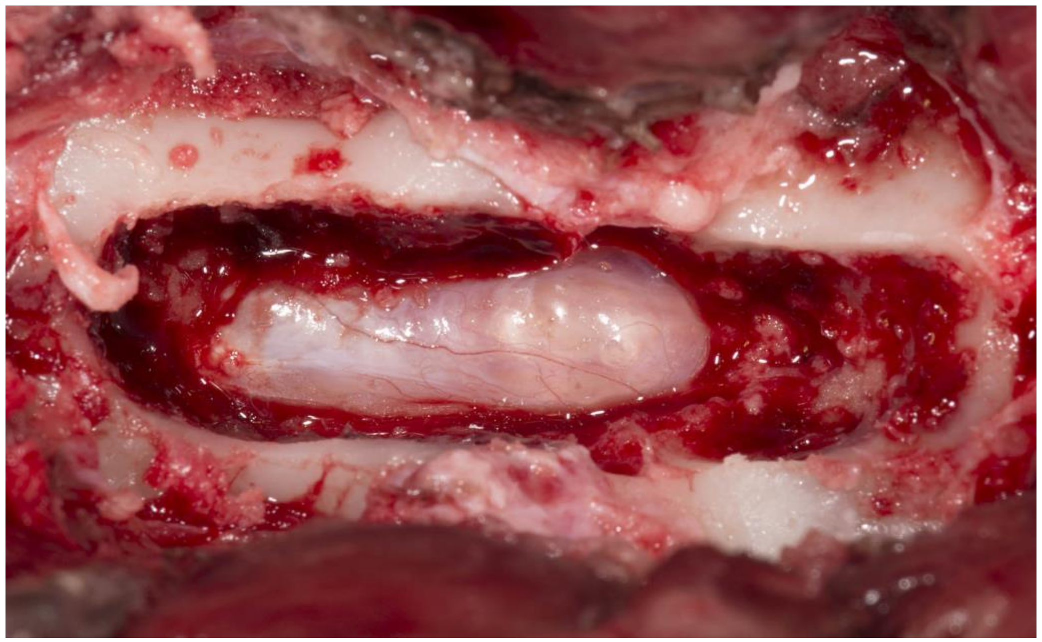


Figure 6. Intradural arachnoid cyst exposed after dorsal laminectomy (top) and resected in toto (bottom)

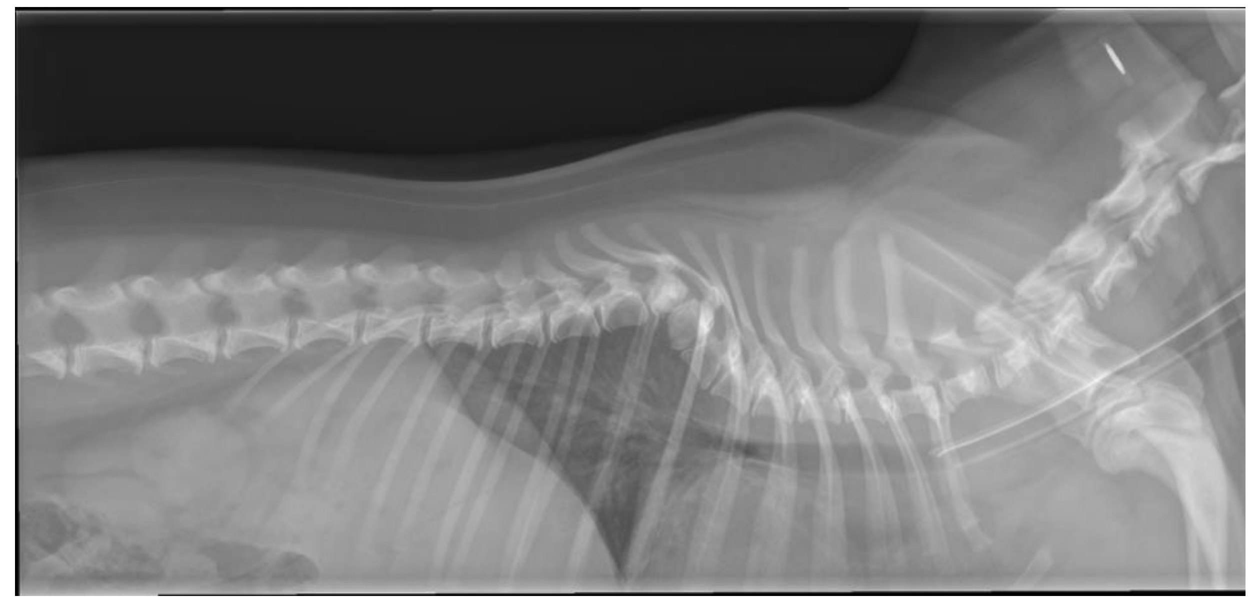


Figure 7. Congenital spinal deformity in a 8-month old pug with severe kyphosis at T8.

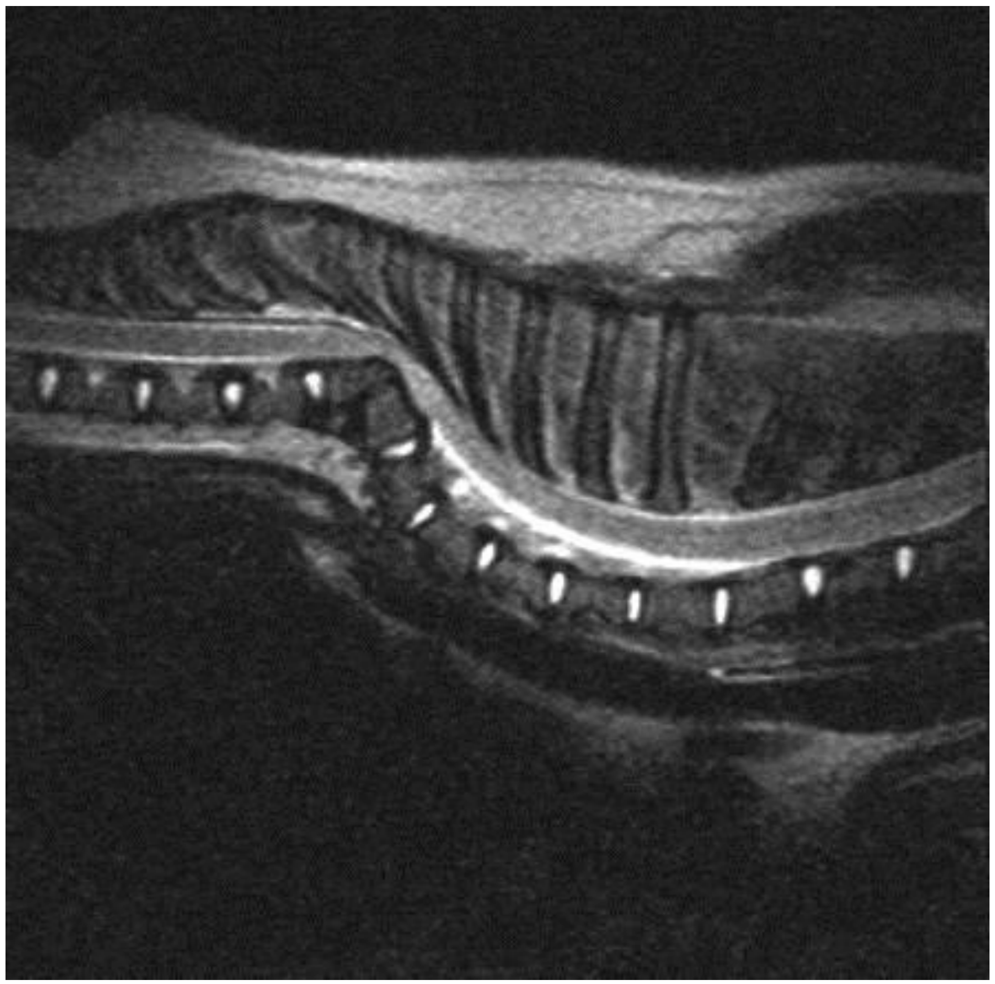


Figure 8. T2W MRI showing the compressive and pinching effect of the spinal deformity on the spinal cord.

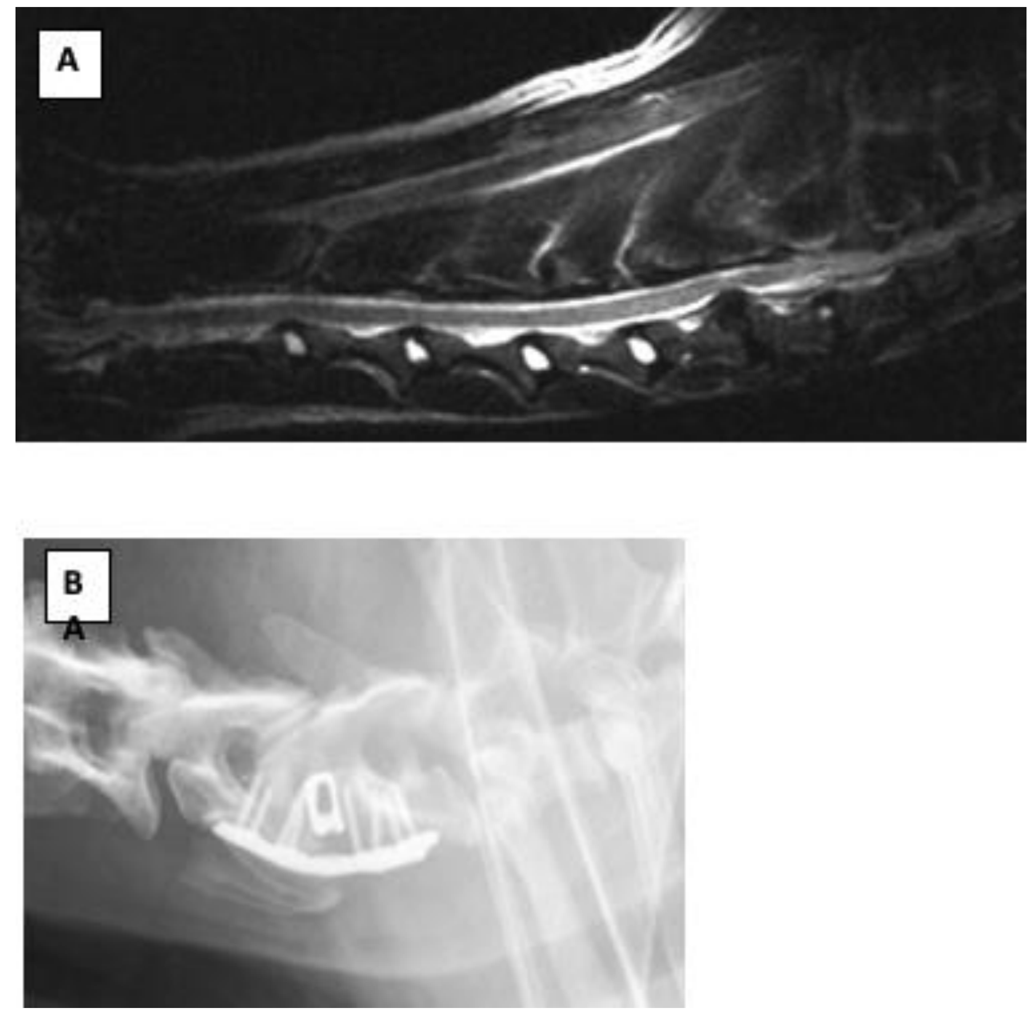


Figure 9.
A) T2W-weighted MR imaging of a 6-year-old Weimaraner with caudal cervical spondylomyleopathy of C6-C7.
B) Distraction and fixation-fusion with intervertebral titanium cage and double locking plates.