REVIEW

Blood Supply to the Human Spinal Cord. II. Imaging and Pathology

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The blood supply of the spinal cord is a complex system based on multilevel sources and anastomoses. Diseases often affect this vascular supply and imaging has been developed that better investigates these structures. The authors review the literature regarding pathology and imaging modalities for the blood supply of the spinal cord. Knowledge of the disease processes and imaging modalities used to investigate these arterial lesions of the spinal cord will assist the clinician when treating patients with spinal cord lesions. Clin. Anat. 00:000–000, 2013.

Key words: spinal cord; vascular supply; anatomy; nervous system; arteries

INTRODUCTION

The vascularity of the spinal cord is formed by a complex arrangement of blood vessels derived from various sources. Prior studies have investigated the anatomy of these structures in detail (Kadyi, 1889; Craigie, 1931; Dunning and Wolff, 1937; Bolton, 1939; Herren and Alexander, 1939; Suh and Alexander, 1939; Bergmann and Alexander, 1941; Gillilan, 1958; Turnbull et al., 1966; Chakravorty, 1971; Lazorthes et al., 1971; Jellinger, 1972; Schossberger 1974; Tveten, 1976; Thron, 1988; Schalow 1990; Lo et al., 2002; Biglioli et al., 2004; Siclari et al., 2007; Becske and Nelson, 2009). Until recently, imaging modalities have been poor at demonstrating the anatomy of the arterial supply to the spinal cord. With improved technologies, however, this part of the central nervous system is now more visible than ever. These improvements in imaging modalities have allowed for more accurate diagnoses of pathologies affecting the spinal cord.

Imaging Modalities

The diagnosis and management of vascular malformations of the spine and spinal cord have undergone significant progress since they were first recognized as a clinical entity in the 19th century. The precise preoperative delineation of the angioarchitecture of spinal cord vascular lesions, however, did not take place until the development of selective spinal angiography. Additional advances in nonionic contrast media, real-time digital subtraction fluoroscopy, and catheter technology have made spinal angiography safer and more sensitive in detecting vascular disease (Prestigiacomo et al., 2003). To develop novel imaging techniques that are able to visualize the most relevant spinal cord arteries and veins, there are at least three requirements that must be met: spatial coverage, spatial resolution, and temporal resolution. Improving one of these items generally degrades one or both of the other requirements (Backes and Nijenhuis, 2008).

Conventional angiography (Fig. 1) is limited by its inability to clearly delineate the location of some vascular malformations in relation to the spinal cord (e.g., perimedullary versus intramedullary). Although conventional magnetic resonance imaging (MRI) can be quite helpful in determining the anatomic

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Fig. 1. Digitally subtracted spinal angiogram demonstrating the artery of Adamkiewicz arising from the left thoracic 9 intercostal artery.

relationships of a malformation with the spinal cord and surrounding structures, it cannot clearly differentiate between artery and vein. Therefore, spinal angiography remains the reference standard. Its high-resolution dynamic imaging provides a vast amount of information that cannot be easily attained from less invasive techniques (Prestigiacomo et al., 2003).

Usually, the standard MRI (Fig. 2) examination is sufficient to raise the suspicion of a spinal vascular malformation. However, neoplasia or inflammation of the spinal cord may mimic the presentation of a vascular lesion. The only technique that is sufficiently reliable to localize and characterize vascular malformations is catheter angiography, also referred to as digital subtraction angiography (DSA) (Backes and Nijenhuis, 2008).

Although CT angiography and MR angiography provide excellent anatomic definition of intracranial vascular lesions comparable to that of DSA, these modalities have not been well developed for the evaluation of spinal vascular lesions. The size of feeding vessels to these malformations is usually beyond the resolution of these modalities (Prestigiacomo et al., 2003). Image quality, in terms of spatial and temporal resolution, is better for catheter angiography when compared with MR or CT angiography. Thus, the first criterion for a novel imaging technique is high spatial resolution, which is required for visualization in light of the fact that spinal cord arteries and veins have submillimeter to millimeter calibers (Backes and Nijenhuis, 2008).

Selective catheterization of arteries feeding the spinal cord carries the risk of neurologic complications. The location of the artery supplying the arteriovenous shunt is not known before angiography, and there are no MR-based predictors, such as location and extent of the cord edema, for the level of the shunt (Gijsen et al., 2007). Therefore, to localize the possible feeding artery or arteries, selective catheterization of all arteries potentially supplying the spinal cord and its meninges may be required. Consequently, lengthy and occasionally multiple catheterization sessions are required, with high radiation exposures in which large volumes of potentially nephrotoxic contrast agents are administered (Gijsen et al., 2007).

Despite its superior spatial resolution and image quality, catheter angiography has several major drawbacks. It is invasive, involves exposure to ionizing radiation, and has a small risk of dislodging aortic thrombi. Catheter angiography is time consuming, may require a number of diagnostic sessions, and requires advanced training and experience. Moreover, catheter angiography can be difficult to perform in patients with aortic diseases, such as aortic aneurysms (Backes and Nijenhuis, 2008).

Recently, three-dimensional (3D) rotational acquisition and reconstruction angiography (Fig. 3) has given investigators the ability to better understand the relationships that exist when studying aneurysms and other vascular anomalies. Three-dimensional rotational spinal angiography (3D-RSA) provides a high-resolution 3D representation of spinal angioanatomy and the vessel location relative to the spinal cord and surrounding structures (Prestigiacomo et al., 2003).

There are limitations to 3D-RSA. One of these limitations is due to notable changes in penetration that occur when performing rotational angiography of the upper thoracic levels at the approximate level of the shoulders. Although spatial resolution is <1 mm, it is still inadequate to discern some normal caliber spinal vasculature (Zarins et al., 1983). As with conventional angiography, the use of 3D-RSA does not demonstrate

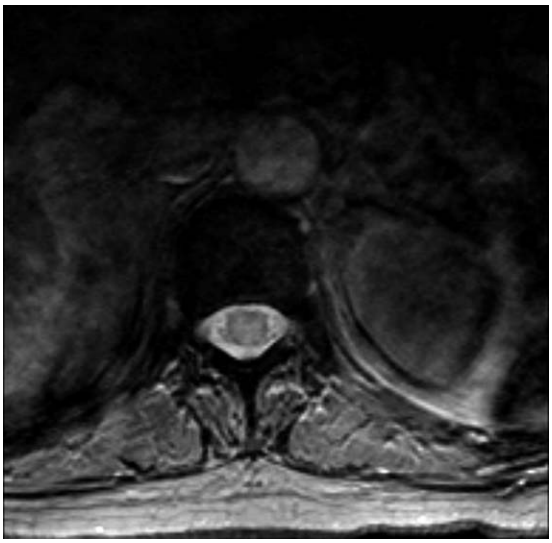

Fig. 2. T2-weighted spinal MRI demonstrating cord edema.

Fig. 3. The 3D reconstruction of cervical dural arteriovenous fistula fed from a third cervical segmental branch. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

all feeding vessels to an arteriovenous malformation with a single injection. Unlike conventional angiography, no temporal resolution exists when performing 3D-RSA; therefore, 3D-RSA cannot be used to determine whether there is increase in transit time within the anterior spinal artery. Although this lack of temporal resolution is a drawback of 3D-RSA, its use in conjunction with conventional DSA images helps to better distinguish between arterial and venous anatomy. Thus, 3D-RSA does not supplant the use of conventional spinal angiography, rather 3D-RSA is intended to improve the interpretation of conventional spinal angiography by reducing, and at times eliminating, various oblique projections needed to interpret the anatomy in three dimensions (Rodriguez-Baeza, 1991).

The introduction of MRI has revealed vascular lesions not seen on angiography, such as cryptic vascular malformations, also known as angiographically occult vascular malformations. Cryptic vascular malformations may cause seizures, repetitive bleeding, neurologic deficits, and, in some cases, death (Edwards and Halbach, 1993). MRI by virtue of its ability to contrast soft tissues is widely applied in patients suspected of harboring spinal vascular abnormalities. Diagnosis based on MRI in these patients is predominantly based on changes of the cord tissue appearance, not on direct visualization of abnormal vessels. Because of this, catheter angiography is the ultimate imaging technique for diagnosing, localizing, and classifying spinal vascular lesions (Anderson and Willoughby, 1987).

A decade ago, traditional MR angiographic techniques were not able to depict normal intradural arteries and were restricted to the visualization of pathologically dilated arteries and veins. Recent advances in MR and CT angiography techniques have strongly improved vessel-to-background contrast by using fast acquisition in combination with contrast agent bolus injection and are now able to depict and differentiate normal spinal cord arteries and veins (Siclari et al., 2007).

Previous approaches with MR angiography (Fig. 4) techniques, including contrast-enhanced time-of-flight (TOF) and phase-contrast angiography (PCA), offered sufficient spatial resolution, but were not able to depict the normal arteries of the spinal cord. The vessel-to-background contrast for both TOF and PCA strongly depends on vessels possessing high blood flow. However, flow in normal intradural vessels is too low to provide sufficient signal intensity changes (Backes and Nijenhuis, 2008).

Because MRI is the primary means of noninvasive screening for vascular lesions and determining who will require invasive catheter angiography for definitive diagnosis and possible treatment, the subtle findings must be detected and the complexities must be clarified as much as possible. The key to differentiating vascular lesions from nonvascular inflammatory, neoplastic, degenerative, and post-traumatic conditions is the identification of vessels with abnormal morphology and hemodynamics (Bowen, 1999).

The two main goals of spinal MR angiography as an adjunct to routine MR imaging have been to improve the visibility of the millimeter-sized intradural vessels and to differentiate abnormal vessels from normal vessels (Kawaharada et al., 2004). Currently, two contrast-enhanced MR angiographic approaches appear successful for the localization of the artery of Adamkiewicz. One technique uses a strong (i.e., temporarily high concentration) bolus, of which the first passage is mainly exploited for imaging during a period of 20–40 sec. In the second approach, a long and slow contrast injection is used with long acquisition times of 4–6 min. The strong bolus technique may provide separation of intradural arteries and veins, whereas the slow bolus technique does not allow for this differentiation (Lasjaunias and Berenstein, 1990).

Differentiation between an inlet artery and an outlet vein is possible by noting relative signal intensity changes: the artery should be brightest in the first phase, and its intensity should decrease in the second phase; the intensity of the vein should increase from the first to the second phase. The contrast between arteries and veins increases with vessel caliber and is, therefore, better for larger (typically extradural) than for smaller (intradural) vessels (Lasjaunias and Berenstein, 1990).

Paraplegia and paresis secondary to spinal cord ischemia remain serious complications of surgical repair or endovascular treatment of descending thoracic or thoracoabdominal aortic aneurysms. The incidence ranges between 5 and 11% of thoracoabdominal surgeries (Skinhoj, 1954). One possible cause of spinal cord ischemia during surgery is failure to reestablish the spinal cord blood supply, and thus many reports have stressed the importance of

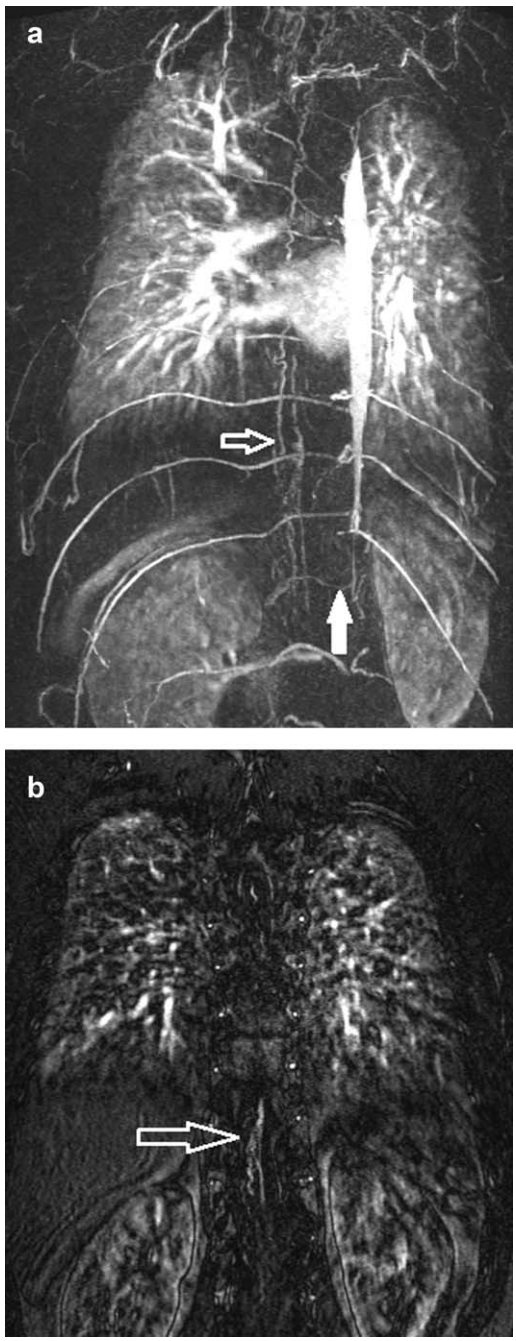

Fig. 4. **a**: The 3D MR angiogram reconstruction demonstrating aorta, intercostal arteries, and finally, a spinal dural arteriovenous fistula. The open arrow demonstrates the draining vein. The closed arrow demonstrates the feeding artery. **b:** Coronal MR angiogram demonstrating an anterior spinal dural arteriovenous fistula (open arrow).

reattaching the intercostal or lumbar arteries related to the artery of Adamkiewicz, the dominant feeder of the spinal cord (Hughes and Brownell, 1964). Preoperative identification of this artery and display of intercostal and lumbar arteries help surgeons to determine the appropriate range of aortic lesions requiring graft replacement and intercostal or lumbar arteries requiring reconstruction (Uotani, 2008).

Kawaharada et al. (2004) first related the clinical outcome in terms of paraplegia incidence to preoperative localization of the artery of Adamkiewicz. In this study of 86 patients, during surgery, only the segmental artery that supplied the artery of Adamkiewicz was reconstructed when it existed in the region of graft replacement (Schossberger, 1974). Paraplegia developed in 2 of 16 patients in whom the artery of Adamkiewicz was not identified. In the remaining 70 patients, the artery of Adamkiewicz was identified and no complications of paraplegia occurred (Backes and Nijenhuism, 2008).

Thus, preservation of the artery of Adamkiewicz is relevant to avoiding spinal cord ischemia. Noninvasive localization of the artery of Adamkiewicz is expected to help reduce the incidence of paraplegia. Although catheter angiography carries a small risk of severe complications (1.2%), this is significant compared with the currently achievable rates of paraplegia in aortic aneurysm surgery (3–5%). Furthermore, identification of normal arteries and veins in patients with spinal vascular malformations could add confidence to what is classified as abnormal vasculature in the spinal cord. Identification of the normal artery of Adamkiewicz should avoid disastrous embolization of this vessel during endovascular treatment of vascular malformations (Prestigiacomo et al., 2003; Na et al., 2007).

The most reliable way to visualize the artery of Adamkiewicz is with the use of selective spinal angiography, the detection rate of which is 43–86%. However, selective angiography is time consuming, and complications such as spinal cord injury can develop. Furthermore, the artery of Adamkiewicz could not be identified in many aortic aneurysm patients by using catheter angiography. Nijenhuis and Backes (2009) argued that the lack of sensitivity of catheter angiography in these patients is because many segmental arteries are occluded by atherosclerosis. The artery of Adamkiewicz and its continuity with the aorta can be obscured.

Recently, CT angiography has been used to visualize the artery of Adamkiewicz less invasively with reported detection rates of 68–90% (Uotani, 2008). Robust aortic contrast enhancement is necessary to detect small vessels, but CT angiography with intravenous contrast injection (IVCTA) (Fig. 5) has limitations with respect to elevating aortic enhancement, because contrast material is diluted in the circulation of the right side of the heart. CT angiography with intra-arterial contrast injection (IACTA) could track the artery of Adamkiewicz to the aorta because of high contrast (Uotani, 2008). The preoperative detection of the artery of Adamkiewicz brings to light the second criterion for novel imaging techniques, which is a large craniocaudal field of vision (up to 50 cm). This field of vision is required because the artery of Adamkiewicz may originate from any segmental artery of the thoracolumbar region, and its location varies between

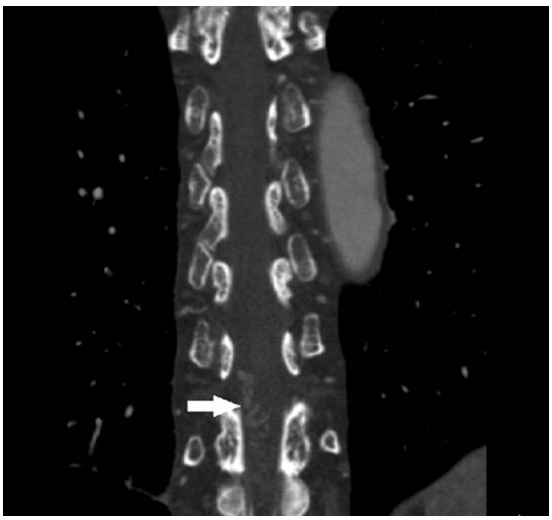

Fig. 5. Coronal reconstruction of spinal CTA demonstrating a spinal dural arteriovenous fistula.

individual patients. However, large fields of view limit spatial focusing (i.e., achieving high spatial resolution) (Uotani, 2008).

Uotani et al. (2008) compared the abilities of IACTA and IVCTA to detect the artery of Adamkiewicz in 32 consecutive patients with thoracic or thoracoabdominal aortic aneurysms who were scheduled for surgical repair or endovascular stent-graft treatment. In this study, the artery of Adamkiewicz was detected more sensitively by IACTA than by IVCTA, and the intercostal and lumbar arteries were displayed more clearly by IACTA than by IVCTA. Furthermore, aortic visualization is enhanced by IACTA because contrast material is directly injected without dilution into the circulation of the right heart.

Arterial catheterization causes IACTA to be more invasive than IVCTA and MR angiography, but IACTA is nevertheless safer and less time consuming than selective spinal angiography, which is associated with complications such as retroperitoneal bleeding, cerebral ischemia, renal failure, and spinal cord ischemia in 1.2–4.6% of patients. Nijenhuis and Backes (2009) critiqued some of the conclusions of the Uotani et al. (2008) study. In the study, continuity between the artery of Adamkiewicz and the segmental artery could not be visualized in all cases, possibly because of the proximity of vertebral bony structures with similar signal intensity on CT scanning. However, occlusion of the segmental artery might also be a possible explanation. Two-thirds of the patient population had an atherosclerotic aortic aneurysm, but an indirect supply to the aorta was not visualized in any of the patients in the study. This finding is interesting because, in other studies, it has been found that the segmental artery directly connecting to the artery of Adamkiewicz was occluded in up to 40% of patients. In these cases, the supply of the artery of Adamkiewicz was provided through an open segmental artery originating one or more levels above or below the occluded segmental artery. There are alternative routes by which the anterior spinal axis might be supplied. Spinal cord function is not always crucially dependent on a segmental supply directly connecting to the artery of Adamkiewicz (Schalow, 1990). Collaterals can maintain spinal cord function. Recently, these collateral pathways have been visualized with MR angiography and correlated with intraoperative spinal cord motor-evoked potentials. Additionally, MR angiography is a less invasive modality capable of visualizing the artery of Adamkiewicz with reported detection rates of 67–93% (Uotani, 2008). As observed in a separate study, when the segmental supply to the artery of Adamkiewicz was inside the cross-clamped aortic region and connecting collaterals originating from outside the cross-clamped aortic area were noticed, this had a predictive value of 97% for stable spinal cord function. This finding can be of crucial importance for the surgeon during both preoperative and intraoperative strategic planning. Therefore, preoperative imaging in thoracoabdominal aortic aneurysm surgery should not only locate the artery of Adamkiewicz with its segmental supply, but should also locate the possible collateral supply (Backes and Nijenhuis, 2008; Nijenhuis and Backes, 2009).

A multiphase approach is necessary to convincingly separate the artery of Adamkiewicz from the outlet vein, or radiculomedullary vein (Lasjaunias and Berenstein, 1990). Reliable differentiation between the artery of Adamkiewicz and the radiculomedullary vein is the third criterion for a novel imaging technique, and this differentiation can only be based on temporal differences in the arrival and transit time of a contrast bolus (Backes and Nijenhuis, 2008). Radiculomedullary veins can have a similar shape to the artery of Adamkiewicz and can run close to the radiculomedullary arteries at the level of the vertebral foramen (Rodriguez-Baeza et al., 1991). Thus, they can be enhanced in the first phase image because of a scan duration of 20–25 sec, whereas the estimated interval between the arterial and venous phases is 10 to 15 sec. Without multiphase dynamic scanning, such vessels might be misdiagnosed as arteries if continuity with intercostal or lumbar arteries is not confirmed. Confirmation of continuity between the aorta and the artery of Adamkiewicz by multiphase scanning is critical to avoid misdiagnosis (Rodriguez-Baeza et al., 1991). Catheter angiography's sensitivity in detection of the Adamkiewicz artery is too variable and too low (43–86%) (Backes and Nijenhuis, 2008).

On the other hand, CT angiography exposes the patient twice to a high effective dose of radiation. A smaller vertebral coverage of T7 to L3 advocated by Uotani (2008) can be used to lower the effective dose. However, Nijenhuis and Backes (2009) argued that this is not an option because of the possibility of missing the location of the artery of Adamkiewicz and its indirect segmental supply. Moreover, such a protocol is insufficient because collaterals most often originate from the pelvic circulation (Nijenhuis and Backes, 2009). Additionally, the CT angiography protocol delineated by Uotani (2008) did not enable visualization of the collateral supply to the anterior spinal axis and has not yet been validated; thus, its true diagnostic value has to be proven.

The alternative to CT angiography is MR angiography. In the opinion of Uotani (2008), the true diagnostic value of MR angiography regarding detection of the artery of Adamkiewicz is unknown. However, Nijenhuis and Backes (2009) have prospectively validated two-phase MR angiography when compared with digital subtraction angiography regarding localization of the artery of Adamkiewicz. In addition, the detection rate of the artery of Adamkiewicz with use of this MR angiography technique has been shown to be nearly 100% in several studies (Nijenhuis and Backes, 2009).

Another important issue when comparing CT angiography and MR angiography imaging of spinal vascular lesions concerns timing. Most critical for differentiation of spinal cord arteries and veins is the timing of image acquisition relative to the contrast agent arrival. This timing is even more critical for CT angiography than for MR angiography because CT angiography represents a second-based acquisition and is faster per section than MR angiography, which is volume-based (Prestigiacomo et al., 2003).

MR angiography benefits from the fact that strong background suppression techniques are available, which allow the depiction of vessels smaller than the voxel size at acquisition to be depicted. Background suppression could also be realized within CT angiography by acquisition of a precontrast scan and subsequent subtraction from the contrast-enhanced scan. However, this would increase the radiation exposure and increase the noise level. Efficient background tissue suppression techniques within MR angiography are most likely the reason for the better contrast-to-noise ratio obtained in patients for MR angiography relative to CT angiography (Backes and Nijenhuis, 2008).

Alternatively, CT imaging is capable of covisualizing the anatomy (i.e., cord and vertebral bone) in addition to the spinal vessels, which is very helpful in finding the location of the vascular lesion. Because MR angiography aims to suppress the surrounding tissue as much as possible, anatomic information is absent in first-phase images. However, additionally acquired second-phase images will display the delayed enhancement of the venous plexus and the vertebral bodies, which may serve to indicate the location of the lesion (Prestigiacomo et al., 2003).

Another important advantage of current CT systems is the higher spatial resolution compared with MR angiography. A feature for which CT imaging is superior to MR angiography is the fact that the entire spinal cord can easily be imaged. Although current MR systems allow craniocaudal (fast readout direction) fields of vision up to 50 cm, fast MR angiography is hampered by large fields of vision in the orthogonal directions, because these represent the time-consuming phase-encoding directions. Thus, although large axial fields of vision can be realized with MR angiography as well, this modality will proportionally increase scan time and consequently deteriorate arterial contrast. Another important advantage of CT angiography is its generally greater and, therefore, more flexible clinical availability and the three to four times shorter examination time (Backes and Nijenhuis, 2008).

However, a draw back to both CT angiography and MR angiography is that the contrast agent can be problematic. A well-known disadvantage of CT angiography is the administration of an iodine contrast agent, which is potentially nephrotoxic. The recently observed adverse effect of certain gadolinium-related MR contrast media in patients with severely impaired renal function has warranted certain restrictions when using gadolinium-based contrast media for MR imaging (Prestigiacomo et al., 2003).

A distinct disadvantage of CT imaging is the inherent exposure to ionizing radiation. Performing a CT scan of the entire spinal cord amounts to an effective dose of $\sim$20 mSv. Limiting the craniocaudal field of vision to the region where the artery of Adamkiewicz is most likely to be detected would lower the dose to $\sim$15 mSv. In diagnostic radiologic imaging, these estimated doses are exceptionally high. For pediatric patients, current CT systems can modulate the effective tube current to reduce the effective dose to the range of 4–7 mSv (Prestigiacomo et al., 2003).

Pathology

Spinal cord infarction is much less frequent than cerebral infarction, accounting for only 1% of all strokes (Novy et al., 2006). Interruption of the blood supply to the spinal cord results in irrevocable damage to the cord within a very short period of time regardless of the site of interruption. When a segmental vessel is occluded, the greatest damage is located at the level of entrance of the medullary artery, but the changes are also seen in a number of segments above and below (Gillilan, 1958). Furthermore, unlike the cerebral vessels, the spinal arteries run along a mobile structure, which makes them prone to mechanical damage (Novy et al., 2006). The main anatomical results of spinal cord ischemia do not differ appreciably from those of cerebral infarction, and range from acute anoxic neuronal changes to cystic necrosis. The respective patterns of the lesions provide some insight into their pathogenesis. For example, selective gray matter involvement usually suggests impairment of the arterial supply, particularly that located in the major extraspinal arterial channels (e.g., in dissecting aortic aneurysms or clamping of the aorta) (Jellinger, 1972).

Novy et al. (2006) analyzed data for 27 patients with acute spinal cord infarction admitted between 1990 and 2003. In this study, there were 11 men and 16 women; the age range was 19–80 years, and the mean age was 56 years. In this series of patients, two different pathogenetic mechanisms were distinguished: a mechanical triggering factor, and prolonged hypotension or arterial insufficiency (Novy et al., 2006). The most probable cause of infarcts occurring after hypotension or arterial insufficiency (i.e., central and transverse infarcts) seems to be global hypoperfusion of the spinal cord. The infarcts involve the territories of several spinal arteries in the thoracolumbar region. This vulnerability to hypoperfusion is explained by the local high density of motor neurons and by the frequency of atherosclerosis in the aorta and iliac

arteries. In an autopsy series, aortic atherosclerosis showed a correlation with lacunar infarction in the central region of the spinal cord (Chung, 1926). The most probable cause of infarcts occurring after mechanical stress in this series of patients was a lesion of the segmental medullary arteries. In contrast to central and transverse infarcts, the localization of the infarction corresponded to the territories of the segmental medullary artery and spinal branches. Vertebral body infarctions, which can be associated with cord infarction, are another sign of segmental medullary artery occlusion (Novy et al., 2006).

The minute volume of blood reaching the gray matter of the central nervous system must be maintained at a high flow rate to prevent damage to the nerve cells. In a study of the vulnerability of various spinal cord structures to anoxia, Gelfan and Tarlov (1955) found that the motor neuron cell bodies are least resistant, with the interneurons and intramedullary primary afferent neurons following in sensitivity. However, abrupt onset of anoxia by complete ischemia shortened the survival time of all structures. Recovery from lack of oxygen is related to the sensitivity to anoxia, and the degree of recovery is inversely proportional to the length of the anoxic period (Gillilan, 1958).

One of the factors that determine blood flow to the spinal cord is the mean arterial pressure (MAP). The MAP can either be calculated using the equation [Diastolic BP + 1/3(Systolic BP-Diastolic BP)] or using an arterial line. The average MAP ranges from 70 to 100 mm Hg. It is crucial to maintain a MAP in the normal range to avoid ischemic injury to the spinal cord, especially in acute spinal cord injury. Studies have shown that hypotension in acute spinal cord injuries leads to decreased cord perfusion and potential for further cord damage secondary to prolonged ischemia (Neurosurgery, 2002; Ploumis et al., 2010). Therefore, the recommendations are to avoid hypotension and maintain a MAP above 85–90 mm Hg in the beginning stages of acute spinal injury to avoid further damage. This is accomplished using volume expansion initially and then vasopressors as needed (Ploumis et al., 2010).

Ischemic lesions of the spinal cord present clinically in many different ways. Three principal groups of clinical syndromes can be distinguished: acute infarction of the spinal cord, progressive myelopathy, and intermittent claudication of the spinal cord and cauda equina.

Acute Infarction of the Spinal Cord

Acute spinal cord infarction results from sudden local interference with spinal blood flow due to occlusion or stenosis of spinal arteries and their afferent channels, including the aorta. The clinical picture depends on the level and on the affected territory in the cord (Martirosyan et al., 2011). The syndrome of the anterior spinal artery is an example of such a clinical syndrome.

The occlusion of the anterior spinal artery is what produces this well-recognized clinical syndrome. The picture of sudden paraplegia; loss of pain, fever, and general tactile sensibility; and the retention of proprioceptive, fine tactile, and vibratory sensibility is seen in occlusion of this vessel. There are variable degrees of a lower motor neuron type of flaccid paralysis, the amount depending on the extent of the involvement of the gray matter in the anterior horn. Because the anterior spinal artery functions is the main source of blood to the posterior spinal arteries below the upper thoracic level, partial occlusion of the anterior spinal artery may cause not only an interference with the blood supply to the anterior surface of the spinal cord below the level of the lesion, but also an ischemia of the posterior surface of the cord to a level above that of the site of the lesion. The result would be an alteration or loss of sensation at levels higher than that of the actual site of the lesion and the clinical symptoms mentioned above. Causes for the occlusion of the anterior spinal artery include diseases of the blood vessels; hypotension with thrombosis; obstruction by tumors, intervertebral discs, bony spurs, and bone fragments; blood, air, and fat emboli; and toxins (Spiller, 1908; Skinhoj, 1954; Hughes and Brownell, 1964; Infante and Alter, 1970; Cheshire et al., 1996; Biglioli et al., 2004; Novy et al., 2006). Because of the variability of areas supplied by the anterior spinal artery, pathological reports can include: destruction of most of the posterior columns, destruction of the medial portion of the posterior columns, and preservation of the posterior columns (Schalow, 1990; Siclari, 2007).

Progressive Myelopathy

Progressive arteriosclerotic myelopathy of the aged is characterized by an ill-defined clinical picture showing 1 of 3 courses: a chronic progressive course with motor neuron disorders, a chronically remittent course with paraparesis or tetraparesis and combined signs of upper and lower motor neuron lesions progressing to incomplete sensory/motor transverse syndromes, or acute recurrent paraplegia; the third course is rare compared to the first 2 noted (Spiller, 1908).

Intermittent Claudication

Intermittent claudication of the spinal cord due to transient ischemia of the lumbar spinal cord in aortic disease is characterized by transient weakness of the legs with or without pain. This clinical syndrome should not be confused with either true intermittent peripheral claudication in occlusive aorto-iliac disease or with intermittent claudication of the cauda equina due to a narrow spinal canal or prolapsed intervertebral disc that is characterized by a particular type of intermittent sensory/motor syndrome of the cauda equina (Skinhoj, 1954).

The arterial supply of the spinal ganglia, as noted earlier, may be considered to be rather vulnerable. There may be some relation between this fact and the frequent occurrence of cellular loss in the spinal ganglia, reduction in the number of posterior root fibers, and mild degeneration of the posterior column in an

otherwise normal spinal cord after the third decade of life, a concept that is further substantiated by the gradual reduction of sensation, most readily discernible as a reduction of vibratory sense, from the third decade of life on (Bergmann and Alexander, 1941).

The relatively poor blood supply of the thoracic region of the spinal cord has been blamed for the frequency with which this region is the site of the lesion in air embolism, as well as its vulnerability to certain toxins and in pernicious anemia. However, the blood supply to the thoracic cord is entirely adequate for the volume of gray matter present, and it is relatively as good as for any other cord segment (Shamji et al., 2003).

The only instance reported where the size of the arteries to the spinal cord is radically altered during life is in coarctation of the aorta, in which all vessels above the coarctation, including those at corresponding segments of the spinal cord, become enlarged in adults (Schalow, 1990). That portion of the spinal cord lying above the level of the coarctation is adequately furnished with blood at high pressures (Tator and Koyanagi, 1997). The lower portion of the cord may suffer from chronic hypotension and from a less than normal blood supply (Zarins et al., 1983).

Surgical procedures can interfere with the blood supply to the spinal cord. Any procedure that exposes the segmental arteries potentially endangers the spinal cord blood supply. These procedures include sympathectomy and splanchnicectomy, thoracic surgery (e.g., lobectomy), and aortic grafting for coarctation and for aneurysm. Aortic aneurysms can dissect posteriorly and tear the ostia of the segmental arteries (Tator and Koyanagi, 1997; Shamji et al., 2003; Siclari et al., 2007). It was mainly from clinical research in aortic aneurysm surgery that the request came to develop noninvasive visualization of normal arteries supplying the spinal cord to avoid the risk of paraplegia induced by disruption of the spinal cord blood supply (Levy and Strauss, 1942; Lo et al., 2002; Na et al., 2007).

Yoss (1950) attempted to correlate the anatomic findings of previous studies of the blood supply to the spinal cord with the clinical picture in vascular disease of the spinal cord and produced experimental vascular lesions of the spinal cord in the *Macaca mulatta*. Sahs (1942) found that the vascular supply of the spinal cord of monkeys and humans is essentially the same. Lesions were induced in the monkeys including: occlusion of an anterior radicular artery, occlusion of the anterior spinal artery, and occlusion of the posterior spinal arteries. The previous sentence and the following discussion of the experiment employ the term "radicular artery" to refer to a segmental medullary artery.

There is marked variation in the number of anterior radicular arteries. More disastrous effects are to be expected from the occlusion of an anterior radicular artery if the number of such arteries is small. The results of occlusion of a larger vessel, such as the artery of Adamkiewicz, will be more serious than the occlusion of a smaller significant radicular vessel. In aortic compression or in a dissecting aneurysm of the aorta, several of these anterior radicular arteries are affected, and an extensive degeneration of the spinal cord will result if the ischemia is prolonged. There are anastomotic pathways among the anterior radicular arteries. However, these alternate channels are not always adequate, and sometimes a relative or absolute ischemia results. It is thought that obstruction of the artery of Adamkiewicz will always cause spinal cord changes of various degrees. Also, the obstruction of other anterior radicular arteries may cause an anoxia of the spinal cord if there are not enough other significant radicular arteries to sustain anastomotic blood flow around the obstructed vessel (Yoss, 1950).

Surgery within either the thoracic or abdominal cavities could affect the artery of Adamkiewicz depending on its level of origin. The first portion of this vessel is well protected in the abdominal cavity from most surgical procedures. Some of the anterior radicular vessels may be occluded without disastrous results. The tip of the spinal cord usually ends between the first and second lumbar vertebrae; therefore, injuries involving the region below the first lumbar vertebra might cause obstruction to an artery of Adamkiewicz arising in this region with involvement of the spinal cord. Traumatic obstruction of this vessel at its origin will cause a vascular lesion of the spinal cord considerably cephalad to the area of trauma (Yoss, 1950).

Levy and Strauss (1942) reported myelopathy secondary to aortic compression at the level of the third lumbar vertebra. There is a great similarity between the clinical picture seen in cauda equina injuries and that produced by obstruction of the artery of Adamkiewicz at lumbar levels. Therefore, the differentiation might be difficult. Occlusion of the artery of Adamkiewicz can result in a lower motor neuron type of paralysis, similar to the paralysis seen in cauda equina injury (Yoss, 1950).

If the vascular occlusion is well above the lumbar enlargement in the spinal cord, only the segment of the cord directly affected by the occlusion will degenerate, with no destruction of the gray matter occurring at the lumbar levels. The descending fiber tracts will be interrupted in the anterior and lateral white columns, and paraplegia will result. The paralysis is usually of the spastic upper motor neuron type. The anterior white columns are essential for the acute development of hyperactive muscle stretch reflexes, clonus, and pathologic plantar reflexes (Crosby and Gillilian, 1962).

If the vascular occlusion is in the lumbar region of the spinal cord and below the entrance of the artery of Adamkiewicz, the caudal portion of the spinal cord will be cut off from its main source of arterial blood. The gray matter in this distal portion of the spinal cord will degenerate with a resulting lower motor neuron type of paralysis of the lower extremities (Schossberger, 1974).

There may also be involvement of some lateral white column fibers with resulting motor weakness. If the occlusion is of sufficient length, occlusion of the posterior spinal arteries will cause destruction of the posterior white columns with loss of proprioceptive, fine tactile, and vibratory sensibility below the level of the lesion. The posterior spinal arteries vary in their distribution, so that in some cases, they supply the posterior portion of the lateral white columns. A case

reported by Chung (1926) that involved paraplegia following thrombosis of the posterior spinal arteries, lends support to this statement. In a monkey that underwent occlusion of the posterior spinal arteries for a distance of 5 mm, there was degeneration primarily in the posterior portion of the lateral white column. In a monkey that underwent occlusion of the posterior spinal arteries for a distance of 1 cm, there was degeneration of fibers in the posterior columns. Evidently, because of the pial anastomoses from the posterior spinal arteries, a segment ~1 cm in length must be occluded to cause an ischemia of the posterior columns. MacNalty and Horsley (1909) reported that occlusion of the posterior spinal arteries can produce lesions in the dorsal spinocerebellar tracts. These lesions produce clumsiness.

Among the vascular lesions of the spinal cord and its meninges, arteriovenous shunts (i.e., spinal arteriovenous malformations and spinal dural arteriovenous fistulas) are the most prevalent abnormalities (Krings and Geibprasert, 2009). If not treated properly, arteriovenous shunts can lead to considerable morbidity with progressive spinal cord symptoms and myelopathy (Backes and Nijenhuis, 2008).

Hemangioblastomas are vascular tumors that can be found throughout the central nervous system; they account for ~2% of primary spinal cord tumors. They are benign neoplasms (World Health Organization Grade I), but they can cause significant morbidity and mortality (Na et al., 2007). Von Hippel-Lindau (VHL) disease denotes an important subset of patients who present with hemangioblastomas in the central nervous system. Hemangioblastomas of the spinal cord occur more commonly as sporadic isolated lesions (70–80% of cases) than as multiple lesions in the cerebellum and retina as part of VHL disease (Na et al., 2007). Magnetic resonance imaging is a useful examination for diagnosis of hemangioblastomas of the spinal cord. Many of these tumors originate in the region of the dorsal roots or at the dorsal root entry zone of the spinal cord (Na et al., 2007).

CONCLUSION

Knowledge of the disease processes and how it presents will assist the clinician in treating patients with spinal cord lesions. Additionally, knowledge of the imaging modalities used to investigate arterial lesions of the spinal cord, specifically their strengths and weakness, will aid the physician in choosing the correct study to investigate the patient's problem. This will help the physician come to an accurate diagnosis sooner and implement time-dependent treatments for arterial lesions of the spinal cord. Moreover, it will also help the patient avoid unnecessary exams and their associated costs.

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