Definitive management of SCI remains illusory, despite intense research efforts and the ongoing development of technology. Ischemia is recognized as one of the most important factors determining the severity of SCI and clinical outcome. The following review discusses the current understanding of the structure and function of the vasculature in normal and injured spinal cords.

Spinal Cord Vasculature

Arteries of the Spinal Cord

The intrinsic arteries of the spinal cord can be separated into a central and a peripheral system. The central system, which supplies two-thirds of the spinal cord, is derived from the ASA and its blood flow is centrifugal. This system supplies the anterior gray matter, anterior portion of the posterior gray matter and posterior white columns, inner half of the anterior and lateral white columns, and base of the posterior white columns. In the peripheral system, the blood flows centripetally from the PSAs and pial arterial plexus. This system supplies the outer portion of the anterior and lateral white columns and the posterior portion of the posterior gray matter and posterior white columns.

The central and peripheral arterial systems have no precapillary interconnections. Their terminal branches overlap, however, allowing regions of the spinal cord to receive blood from both systems. This overlap occurs within the inner first one-quarter to first one-third of the white matter and within the outer edge of the gray matter. The exceptions are the posterior halves of the posterior horns, which are supplied entirely by the peripheral system. The widest internal overlap occurs in the posterior and lateral columns. Extrinsically, the anastomosis between the systems is greatest around the tip of the cauda equina. Although there is some overlap between the systems, because blood flows away from the center in the central system and toward the center in the peripheral systems, their relationship is not truly compensatory. The various regions of the spinal cord are disproportionately vascularized, and the ratio of blood supplied by the central system to the peripheral system is not constant throughout the cord: The cervical region has a large peripheral and large central arterial supply, the thoracic region has large peripheral and small central supply, and the lumbar and upper sacral regions have a small peripheral and large central supply.
Obstruction of an artery feeding the cervical and lumbo-sacral regions seldom results in an infarction, as these areas are well vascularized. The radicular (radiculo-medullary) arteries reaching the upper cervical region are fed by intervertebral branches of the vertebral arteries and their descending rami. In the lower cervical region, the segmental arteries, which feed the radiculo-medullary arteries, arise from the deep cervical artery, the costocervical artery (from the subclavian artery), or the ascending cervical artery. The many interconnections between these arteries and others in the neck allow blood flow despite occlusion in another area. In the lumbar region, arteries extend from the aorta and into the vertebral body wall where radicular arteries arise from them, some of which may be radiculo-medullary arteries. The segmental arteries in the sacral region are supplied with blood from the lateral sacral arteries. These pelvic arteries form numerous anastomoses with other arteries of the pelvis. Therefore, not unlike in the cervical region, a single occlusion of an artery is unlikely to result in ischemia. Because none of the sacral radicular arteries contribute to the ASA or PSA, their obstruction is less threatening.

Due to poor collateralization in the thoracic vascular region, however, compromise of blood flow potentially creates a great risk of ischemia. In the thoracic cord, the distance between sources of blood supply is considerable. The radiculo-medullary arteries feeding the thoracic spinal cord originate from a few intercostal arteries (from the subclavian artery and aorta), and anastomotic connections between the extraspinal arteries supplying this region are scarce. The compensatory support provided in the lumbar and cervical regions does not exist in the thoracic region; consequently, compromise of these arteries results in discreet regions of ischemia.

**Extrinsic Spinal Cord Arteries**

**The ASA.** The ASA, the trunk of the central arterial system, supplies most of the intrinsic spinal vasculature. Occlusion of this artery results in infarction of the anterior two-thirds of the spinal cord (Figs. 1 and 2). Before the vertebral arteries unite to form the basilar artery, both give off a branch and join together and then descend on the surface of the anterior spinal cord as the ASA. Usually, these branches fuse within 2 cm of their origins, but they can remain separated until around the C-5 level. The ASA extends over the length of the spinal cord, ventrally to the anterior median fissure. The diameter of the ASA usually decreases gradually from its origin until it reaches the thoracic region. From the thoracic region down, the diameter of the ASA remains fairly constant. At the lower end of the sacral or coccygeal region, branches from the ASA loop caudally around the conus medullaris and join each limb of the PSA. The trunk of the ASA is then reduced to a tiny vessel, which extends along the conus and the filum terminale (Fig. 2). Because the ASA is an anastomotic channel consisting of terminal branches of successive radiculo-medullary arteries, its size varies in response to its conjunctions. The most striking example is at its junction with the great radicular artery (artery of Adamkiewicz), often at L-1 or L-2 on the left. In the lower thoracic region, before the vessels merge, the ASA becomes so small that it may be indistinguishable from other arteries. At its juncture with the artery of Adamkiewicz, however, the ASA reaches its greatest diameter (Figs. 1 and 2). Although rare, 2 radiculo-medullary arteries may enter a single segment of the ASA from both sides. In this scenario, the shape of the ASA is often rhomboidal, a feature often noted in the cervical region. The ASA is frequently duplicated for short distances in the lower cervical region and is singular in other regions.

**The PSA.** The paired PSAs run longitudinally along the posterolateral surface of the spinal cord medial to the...
posterior nerve roots. The PSA can arise from the vertebral arteries or the posterior inferior cerebellar arteries. Much more rarely, it branches from the posterior radicular artery at C-2. The PSAs swing laterally around the brainstem and then veer posteriorly along the surface of the cervical spinal cord.\(^8\) They are identified as distinct single vessels only at their origin. Thereafter, they become anastomosing channels, largely retaining their embryonic plexiform design.\(^3\)

At the lower end of the spinal cord, the PSAs send out small branches to the proximal part of the posterior rootlets and nerve roots, most often in the roots of the cauda equina.\(^2\) The size of the PSAs varies. At times they become incredibly small, making them impossible to identify.

**Pial Arterial Plexus.** Surface vessels branching from both the ASA and the PSA form an anastomosing network—a pial arterial plexus (vasa corona)—that encircles the spinal cord.\(^3\) Most of the branches from the pial arterial plexus penetrate the dorsal midline of the spinal cord. All of the penetrating branches run directly inward, perpendicular to the surface of the spinal cord. These branches supply the outer portion of the spinal cord, including the greater part of the posterior horns, and extend to the substantia gelatinosa (Fig. 1).\(^8\)

**Radicular Arteries.** Among the 31 pairs of radicular arteries, there are 3 distinct types: 1) some radicular arteries end within the roots or on the dura mater before reaching the spinal cord; some radicular arteries do not penetrate beyond the surrounding arterial systems of the spinal cord; and some radicular arteries actually vascularize the spinal cord (that is, medullary or radiculomedullary arteries). The diversity in the paths of the radicular arteries illustrates their various levels of supply. Radicular arteries supply blood to the dura mater, to the nerve roots that they accompany, to the spinal ganglia, and to the ASA and PSA.\(^5\)

Radiculomedullary arteries are often located on the left side of the thoracic and lumbar regions (where the aorta is left of midline) and are more equally distributed in the cervical region. Left-sidedness size dominance is more pronounced among the anterior radiculomedullary arteries than the posterior radiculomedullary arteries, which nonetheless are still more dominant on the left.\(^3\)

The typical segmental artery, which can originate from various sources (for example, subclavian, aorta), divides into anterior and posterior rami. The posterior ramus splits into a spinal arterial branch and a muscular arterial branch. The spinal branch crosses the intervertebral foramen and divides into anterior and posterior radicular arteries.\(^7\) As noted, not all of these radicular arteries reach the surface arteries of the spinal cord. The radicular arteries that traverse the nerve roots course on the anterior surface. After they reach the nerve root, they become encaised in perineurium and enter the subarachnoid space, where they are loosely attached to the nerve roots. A single radicular artery can become an anterior or a posterior radicular (radiculomedullary) artery or, although rare, divide to become both.\(^8\)

The number of anterior radicular arteries that contribute to the ASA ranges from a minimum of 2 to a maximum of 17 (mean 10). The mean diameter of the anterior radicular artery ranges from 0.2 to 0.8 mm. When the diameter of the artery is smaller than 0.2 mm, it seldom reaches the ASA and usually serves to supply the root.\(^8\)

Each region of the ASA receives different numbers of anterior radicular arteries. The cervical ASA receives a mean number of 0–6, the thoracic ASA receives 1–4, and the lumbar ASA receives 1 or 2. The smaller arteries accompanying the roots of the cauda equina are thought to become more important when large radicular arteries enter the spinal cord at a relatively high position or when they become narrowed. Again, the scarcity of anterior radicular arteries and the extensive distance between them indicate that occlusion of a single artery in the thoracic region can result in ischemia.\(^8\)

Posterior radicular arteries, of which there can be 10–23 (average range 12–16), divide on the posterolateral surface of the spinal cord to supply the ipsilateral PSA. These arteries are smaller than their anterior counterparts. Their diameters range from 0.2–0.5 mm. Posterior radicular arteries can originate as superiorly as C-2 and are more frequent on the caudal portion of the spinal cord, where they are usually narrower. The posterior radicular arteries extend to feed the pial arterial plexus on the lateral aspect of the spinal cord, in addition to the nerve roots, dura mater, spinal ganglia, and PSA.\(^7\)

The number and position of the posterior radicular arteries do not appear to be related to the number and position of the anterior radicular arteries. When anterior and posterior radicular arteries occur at the same level and side, they unite to form a common stem outside the dura.\(^3\)

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Fig. 2. Anterolateral view of lumbar spinal cord. Used with permission from Nicholas Theodore, M.D.
Blood supply of spinal cord

The artery of Adamkiewicz (also called the arteria radicularis magna, the great radicular artery, or the artery of lumbar enlargement) is the largest vessel that reaches the spinal cord. It is 1.0–1.3 mm in diameter, and it supplies a quarter of the spinal cord in 50% of people. In 75% of people, this artery travels with the T9–12 roots. In 10% it follows roots L-1 or L-2, and in 15% it has a high origin at posterior roots T5–8. In this final case, a more caudal supplementary artery called the arteria colliculare is always present. The artery of Adamkiewicz is found on the left side 80% of the time. When it joins the ASA, it branches into a small ascending branch (0.231 mm) and into a large descending branch (0.941 mm) (Figs. 1 and 2).

Fried and Aparicio ligated the artery of Adamkiewicz and the ASA just above and just below the entrance of Adamkiewicz in monkeys to determine how the location of the blockage would alter perfusion of the spinal cord and neurological outcome. When the artery of Adamkiewicz was ligated just above the union of the vessels, neurological deficits were slight. However, ligations above the artery of Adamkiewicz produced mild to moderate chromatolysis and hyperchromatism. When a ligation was placed below the entrance, however, 82% of monkeys became paraplegic. These findings indicate that more caudal regions of the spinal cord rely heavily on the artery of Adamkiewicz for perfusion.

Central Arteries. Adults have a mean of 210 central arteries. The central arteries feed the central area of the spinal cord, which consists of the white matter bordering the central sulcus, the gray matter of anterior horn, and the deep gray matter of posterior horn. Central arteries arise from the ASA and penetrate the spinal cord posteriorly in the anterior median fissure. When central arteries stem from a duplicated portion of the ASA (often in the lower cervical region), they only pass to the side of the ASA from which they arise. Otherwise, when the artery reaches the anterior white commissure, it continues to either side of the spinal cord. Less commonly, it bifurcates and each limb of the vessel retreats to the contralateral side of the spinal cord. Successive central arteries usually alternate sides, but they also can extend to the same side.

On reaching the anterior gray matter, the arteries divide into short ascending and descending branches and into horizontal branches, which often traverse the periphery of the gray matter before they transition into capillaries (Fig. 1).

If the central artery bifurcates, it always does so in the sagittal plane. It cannot be seen in transverse sections. Such bifurcations are least common in the cervical and thoracic regions (9% and 7%, respectively) and slightly more common in the lumbar and upper sacral regions (14% and 13%, respectively) (Fig. 2).

The dispersal and configuration of the central arteries, much like the radicular arteries, can be explained by the relative paucity of gray matter in the thoracic spinal region. There are fewer central arteries in the thoracic region, and they are smaller than those in the cervical and lumbosacral regions. The cervical region has 5–8 central arteries/cm of ASA compared with 2–6 and 5–12 in the lumbosacral region. The mean diameter of the central arteries is 0.21 ± 0.05 mm in the cervical region, 0.14 ± 0.04 mm in the thoracic region, 0.23 ± 0.6 mm in the lumbar region, and 0.2 ± 0.5 mm in the upper sacral region.

In the less crowded cervical and thoracic regions, an acute angle is formed by the emerging central arteries and the ASA. In the lumbosacral region, a right angle is formed. As a result the central arteries in the lumbosacral region extend both horizontally and deeper into the spinal cord than the central arteries in the other regions. This difference is the result of the angles, because the lengths of the central arteries are almost the same (cervical 4.3 ± 1.0 mm, thoracic 4.3 ± 0.9 mm, lumbar 4.7 ± 1.2 mm, and upper sacral 4.4 ± 1.1 mm). In the cervical region, and even more so in the thoracic region, the trunks of the central arteries traverse the spinal cord at an angle, covering the considerable longitudinal distance between arteries. Terminal branches of the central arteries stretch along the length of the spinal cord, overlapping with the territories of neighboring arteries. In the thoracic region, the central arteries send most of their branches longitudinally, whereas those in the cervical and lumbosacral region mainly branch horizontally. A central artery in the thoracic region can cover as much as 3.0 cm in distance. In contrast, it can cover no more than 1.2 cm in the cervical region and no more than 1.7 cm in the lumbosacral region.

Capillaries of the Spinal Cord

As is common in the vasculature of the spinal cord, the white matter is not served by capillary beds as abundantly as it is the gray matter. In fact, the density of the capillary bed is 5 times greater in gray matter than in white matter. The capillary beds in white matter are also fairly uniform, stretching longitudinally in the direction of the nerve fibers. Where the gray and white matter meet, the capillary beds are denser than those in white matter alone. Within the gray matter, the density of the beds depends on the location of the cell bodies. This arrangement reflects the greater metabolic requirements of cell bodies compared with axons.

The lateral horns, anterior horns, and base of the posterior horns (especially the substantia gelatinosa) have the thickest capillary beds, although the remainder of the posterior horns is not well supplied.

Direction of Arterial Blood Flow

The watershed effect occurs when 2 streams of blood flowing in opposite directions meet, as is common in the vascular system of the spinal cord. In a watershed area, the likelihood of the surrounding tissues suffering from occlusion increases. Local pressure from a space-occupying lesion, which may not cause any vascular compromise elsewhere, can result in ischemia in the watershed region.

At the union of a radicular artery and the ASA, the blood courses upward and downward from the entry point. Therefore, in the area of the ASA between neighboring radicular arteries, there is a dead point where blood flows in neither direction, that is, a watershed area. The location of this dead point fluctuates constantly. In the midthoracic area, where the distance between radicular arteries is the greatest, the watershed effect is at its maximum.
The blood flow in the PSA does not mirror that of the ASA. The PSA does not narrow like the ASA and thus does not provide a mechanical barrier to upward flow. When Bolton injected a solution with Indian ink into the vertebral arteries of human corpses and followed its path, the blood running down the PSA reached the highest thoracic segments. At this point, the vertebral blood met the blood flow up from the caudal part of the ASA via 2 terminal branches. These terminal branches pass caudal to the anterior S-5 roots, and each one joins with a single PSA lateral to the fifth posterior sacral roots (Fig. 2). The ascending blood flow of the caudal portion of the PSA is often reinforced by posterior lumbar radicular arteries.

As noted, the artery of Adamkiewicz, the most notable of the radicular arteries, joins the ASA with a small ascending branch and a larger descending branch. Resistance to flow through the upper branch is 278 times greater than in the downward branch, because the diameter of the ascending branch is much smaller (0.231 mm) than that of the descending branch (0.941 mm). Under normal conditions in humans, the ascending branch of the artery of Adamkiewicz is required to supply the arterial domain of the upper 1–3 thoracolumbar segments, and its relatively small blood flow is sufficient. It is likely, however, that under the collateral demands of aortic cross-clamping during surgery, the quantity of blood flow to the higher midthoracic area is unreliable. In the ASA the blood flow may be modified by contraction of the conventional circular muscularization of the tunica media, the generally longitudinally disposed layer of the intimal musculature, and the intimal cushions near and in the critical vascular junction just below the boundary between the thoracolumbar and midthoracic arterial domains.

**Autoregulation**

Autoregulation is the process that ensures constant blood flow when systemic blood pressure or CO₂ concentrations rise or fall. While the blood flow in the spinal cord is 40%–60% that of the brain, the tissue oxygen levels are the same (35–39 mm Hg). The volume of blood perfusing the spinal cord increases when arterial CO₂ tension increases and falls when it decreases. Vasodilation and constriction enable these changes to occur without altering the SCBF.

**Effect of MABP and CO₂ Pressure on SCBF.** Research has been done in various animals to determine the ranges of MABP and CO₂ pressure in which autoregulation is maintained. In sheep, blood flow in the gray and white matter in both the cervical and lumbar regions remains steady when MABP ranges between 40 and 100 mm Hg. Hitchon and associates used lambs to measure SCBF, because the white and gray matter in their spinal cords are markedly distinct. When MABP was between 100 and 40 mm Hg, SCBF in the cervical gray and white matter (124–141 ml/100 g/min and 22–26 ml/100 g/min, respectively) and in the lumbar gray and white matter (74–104 ml/100 g/min and 15–24 ml/100 g/min, respectively) remained fairly stable. When MABP fell below 40 mm Hg, SCBF dropped significantly.

Kobrine and associates found that when CO₂ pressure was between 10 to 50 mm Hg in monkeys, SCBF stayed constant. When the pressure of CO₂ surpassed 50 mm Hg, SCBF increased. Further increases above 90 mm Hg had no effect on SCBF, which had reached a physical maximum. In another study, Kobrine and coworkers found that SCBF remained constant when MABP was between 50 and 135 mm Hg. Below 50 mm Hg, vascular resistance decreased maximally, and SCBF became a function of MABP. When MABP exceeded 135 mm Hg, vascular resistance decreased, vasodilatation occurred, and SCBF increased markedly. These findings are clinically relevant because the capillary endothelium responsible for the normal blood-brain barrier can be disrupted in this hypertensive environment and high SCBF can result in the formation of edema, which can be detrimental to neural function.

**Mechanism of Autoregulation.** In research by Young and associates, cats received paravertebral sympathectomies, adrenalectomies, or both to determine whether paravertebral sympathetic ganglia or the adrenal gland was involved in autoregulation. There was no autoregulation of SCBF in response to systemic pressure changes in cats with sympathectomies, and there was a linear relationship between MABP and SCBF. In the control and adrenalectomy groups, SCBF did not correlate with MABP between 80 to 160 mm Hg. Therefore, the sympathetic ganglia are a necessary component of spinal cord autoregulation. In contrast, Iwai and Monafia found only moderate effects on regional SCBF after they performed lower lumbar sympathectomies in rats.

Proximal transections have been performed to help determine the location of the sensory control center for autoregulation. These procedures do not influence the response of MABP and CO₂, indicating that the sensory control center for autoregulation lies caudal to the medulla. Knots of vessels (glomeruli) exist in and around the capillary beds of the anterior and posterior horns. The capability of these glomeruli to act as sensors to direct autonomic blood flow of the spinal cord is supported by the presence of muscular cushions in the intima of the lower (inferior thoracic and lumbosacral) ASA and their sensory (afferent and efferent) junctions. Glomeruli found in capillary beds within the spinal cord may act as sensors within the spinal cord. One reason for this supposition is that these glomeruli resemble arteriovenous glomerular clumps, which are found in fingers, toes, the penis, and other parts of the body, and act as components of nerve root circulation capable of shunting blood from arteries to veins and bypassing the capillaries. Such shunting can also occur in the spinal cord. Further research is needed to cement this theory.

**Spinal Cord Blood Flow After Thoracic Aortic Occlusion**

**Aortic Cross-Clamping**

During repair of thoracoabdominal aortic aneurysms, temporary aortic cross-clamping decreases SCBF and distal organ perfusion. After an hour of aortic cross-clamping, thoracolumbar SCBF has been reported to decrease from 20 to 1.8 ml/100 g/min.
Blood supply of spinal cord

causes distal hypotension (below the clamp), proximal hypertension (above the clamp), left ventricle afterload, and an increase in CSFP and central venous pressure. It also elevates intracranial pressure. The induction of proximal hypertension and intracranial pressure during aortic cross-clamping prompts the autoregulatory mechanisms of the cerebral and spinal vasculature to increase CSFP reflexively, effectively lowering SCFP and diminishing the blood supply to the spinal cord. Systemically, an SCI causes hypotension not only by interrupting sympathetic fibers but also by direct myocardial dysfunction. With its limited blood supply and the most deleterious watershed effect, the thoracolumbar spinal cord is the portion of the spinal cord at greatest risk for ischemic injury.

Understanding the relationships among distal and proximal blood pressure, CSFP, SCPP, and MABP is necessary to solve the problems that can arise during aortic cross-clamping. Spinal cord perfusion pressure is a key measure used to evaluate the circulation of the spinal cord. It is equal to the difference between the mean distal aortic pressure and CSFP. Spinal cord perfusion pressure must stay above 50–60 mm Hg to protect the spinal cord from ischemia.

Several studies have supported the notion that SCPP is more relevant in determining SCBF than are CSFP and MABP. Griffiths and associates exemplified this point when they raised SCPP significantly (from 5 to 123 mm Hg) in dogs while maintaining CSFP, and they observed a steathy rebound of the SCBF. In this study SCBF autoregulation was lost when SCPP fell below 50 mm Hg. As the SCPP was lowered from baseline to 50 mm Hg, the vascular resistance decreased. Below 50 mm Hg, the resistance was unchanged, perhaps because the vessels were fully dilated and compressed due to CSFP.

Taiira and Marsala correlated proximal aortic pressure with distal aortic pressure during aortic cross-clamping and, after the aorta was unclamped, with proportional decreases in distal aortic pressure and SCBF. When proximal aortic pressure was maintained above 100 mm Hg during aortic cross-clamping, distal aortic pressure was 19 ± 4 mm Hg. When proximal aortic pressure was held at 40 mm Hg, distal aortic pressure fell to 7 ± 1 mm Hg. After the clamp was released while proximal aortic pressure slowly decreased, SCBF also decreased. The decrease in SCBF was 8% ± 4% of baseline values when proximal aortic pressure was held above 100 mm Hg and 2.5% ± 1.6% of baseline values when proximal aortic pressure was 40 mm Hg. Therefore, SCBF can increase as a result of increasing proximal aortic pressure during and after aortic cross-clamping. This point is clinically relevant because at lower proximal aortic pressures neurological deficits were incurred more quickly than at higher proximal aortic pressures. In dogs, Laschinger et al. showed that a distal aortic pressure of 60–70 mm Hg was adequate to maintain spinal cord function during aortic cross-clamping. When distal aortic pressure fell below 40 mm Hg, SSEPs were often lost and an SCI was incurred (66% paraplegia). Maintaining distal aortic pressure above 70 mm Hg uniformly preserved SCBF as long as critical intercostal arteries remained intact.

The direct relationship between CSFP and central venous pressure has been shown in various studies. In dogs, Piano and Gewertz showed that although CSFP and central venous pressure both increased significantly with aortic cross-clamping, the increase in CSFP was always equal to or greater than the venous increase. With volume loading this trend continued, supporting the relationship between CSFP and central venous pressure. The mechanism that links the CSFP and central venous pressure relies on the structure of the venous system of the spinal cord. Radicular veins extend from the sinuoidal channels of the spinal cord and travel through dural space, dura, and epidural fat before joining the larger veins. As the veins traverse this labyrinthine route, they narrow. When CSFP within the tissue of the spinal cord becomes higher than venous pressure, the vein collapses. Outflow resistance and venous pressure then increase.

In humans the normal range of CSFP is 13–15 mm Hg, whereas its range during aortic cross-clamping is 21–25 mm Hg. Berendes et al. found that when CSFP remained below 20 mm Hg in patients during thoracic aortic operations (87.5% [8 patients]), no postoperative neurological deficits were evident. When CSFP exceeded 40 mm Hg during the operation (12.5%), paraparesis developed postoperatively. Blaisdell and Cooley found that when the CSFP was higher than the distal aortic pressure, the incidence of paraplegia increased by 17%.

Molina and associates observed that when the clamp was released after an hour of aortic cross-clamping, CSFP remained elevated for 5 minutes and returned to normal only after another 25 minutes. After the clamp was released, hyperemia was observed in both the gray and white matter from T-12 down. The degree of hyperemia, however, was much greater in the gray matter.

Risks and Neurological Deficits

Much has been learned about vascular reactivity in the spinal cord from thoracoabdominal aortic surgery experience. Neurological deficits are a considerable risk associated with surgeries that employ aortic cross-clamping. Svensson and colleagues reviewed 1509 patients who underwent repairs to treat thoracoabdominal aortic disease of varied severity. Among these patients, the incidence of paraplegia or paraparesis was 16%. In a study of 121 cases of thoracoabdominal aortic aneurysm repair by Cinà and associates, neurological deficits were recorded in 6.2% of patients, and the hospital mortality rate was 21.4%.

The complexity of the repair is a significant predictor of SCI. The Crawford classification system organizes thoracoabdominal aortic aneurysm repairs based on the extent and position: Type I aneurysms extend from the proximal descending thoracic aorta to the upper abdominal aorta; Type II aneurysms from the proximal descending thoracic aorta to below the renal arteries; Type III aneurysms from the distal half of the descending thoracic aorta into the abdomen; and Type IV aneurysms involve most or all of the abdominal aorta. Repairs of Types I, II, III, and IV were associated with rates of paraplegia or paraparesis of 15%, 31%, 7%, and 4%, respectively. In a randomized study, Crawford and associates found that there was a 32% incidence of neurological deficits of
varied severity and duration) affecting the legs associated with Type I and II repairs.

In the 1970s the first attempts at improving thoracoabdominal aortic aneurysm surgery focused on decreasing the duration of surgery. Time is clearly an important indicator of neurological outcome. Repairs requiring more than 60 minutes of aortic occlusion were reported to carry a 20% risk of paraplegia and paraparesis, whereas the risk for a 30-minute occlusion was less than 10%. When spinal cord ischemia was sustained for 50 minutes, the incidence of spastic paraplegia in dogs was 87.5%. During the last 40 years, however, it has become clear that numerous factors influence the neurological outcome of thoracoabdominal aortic aneurysm repairs in addition to the duration of aortic cross-clamping: the extent of the aneurysm, acute dissection, and preoperative problems (that is, renal condition, previous aortic surgery, and diabetes). Preoperative hypotension, distal aortic hypotension after aortic occlusion, the interruption of critical intercostal arteries, and postoperative hypotension or hypoxia can all result in injury. Each of these factors can affect SCBF, the oxygen delivery system to the spinal cord, which is crippling to neurological function. Gharagozloo and colleagues found that SCBF held at 10 ml/100 g/min during aortic cross-clamping resulted in no paraplegia, whereas SCBF reduced to 4 ml/100 g/min resulted in universal paraplegia. This finding illustrates the neurological impact of decreased SCBF.

Not all neurological deficits reveal themselves immediately. The incidence of postoperative paraplegia was 10% in a study by Schepens et al., 21% in a study by Cox et al., and 13% in a report by Crawford et al. Crawford and associates found that 68% of patients who had undergone Type I and II repairs developed neurological deficits. In 32% of the patients with neurological deficits, the paralysis did not manifest for several days. Immediate neurological deficits are a result of the hypoxic environment induced by prolonged aortic cross-clamping and minimal SCBF. Delayed neurological deficits can materialize 1–21 days after surgery. These deficits may be a result of ischemia arising from low SCBF as a result of high vascular resistance and regional hypotension restricting blood flow through the high-resistance vascular plexus of spinal cord or a result of reperfusion hyperemia and free radicals causing spinal cord edema. Barone and associates compared the SCBF and blood pressure of paraplegic and normal dogs during and after surgery. They found that thoracolumbar SCBF in both paraplegic and nonparaplegic dogs was 10%–20% of baseline after 30 minutes of aortic cross-clamping. Thirty minutes after the cross-clamp was released, significant hyperemia was present. After aortic cross-clamping, reperfusion flow in the nonparaplegic dogs was approximately twice that of baseline, whereas in the paraplegic dogs flow was approximately eight times that of baseline.

Avoiding Complications

Various methods have been conceived to improve the neurological outcomes of aortic cross-clamping, although on their own, none of these methods can address all the possible causes of SCI and neurological deficits.

Monitoring and Imaging. Monitoring spinal cord function and using imaging to avoid displacing key radicular arteries are important factors in improving the outcomes of thoracoabdominal aortic aneurysm repair. In patients undergoing surgery to treat thoracoabdominal aortic artery disease and aneurysms, Dong and colleagues found that the use of MEPs to follow spinal cord function was more effective than using SSEPs. The MEPs in 28.6% of their 56 patients showed evidence of SCI, whereas the SSEPs showed such signs in only 25%. In 81.3% of the 28.6% patients, ischemic changes in MEPs were reversed by reimplanting segmental arteries, increasing distal aortic pressure, or using hypothermic conditions.

Kieffer and colleagues found that using spinal cord arteriography to identify the location of the artery of Adamkiewicz before thoracoabdominal aortic surgeries was very useful. When the artery of Adamkiewicz was visualized and originated above or below the clamp area, the duration of surgery decreased and no spinal cord complications occurred. When the artery of Adamkiewicz originated in the clamped section, revascularization was attempted. When revascularization was successful, only 5% of the cases sustained ischemic injury. When it was unsuccessful, 50% developed ischemic injuries. Of the group in which the artery of Adamkiewicz could not be visualized, 60% became paraplegic.

Distal Aortic Perfusion. Distal aortic shunting, as provided by left atrium–femoral artery bypass or a simpler artery-to-artery shunt aims to provide effective control of proximal blood pressure and to avoid a decrease in distal aortic flow. Still ischemia can occur if the arteries supplying the ASA rely on excluded segments of the aorta.

Cerebrospinal Fluid Drainage

Manipulating the CSF compartment whether by pressure or content alteration remains an enticing goal for its potential effect on SCIs. Cerebrospinal fluid drainage has been heavily investigated to identify whether drainage is effective and, if so, when it should be initiated and in conjunction with what other protection mechanisms. Proximal hypertension induced by aortic cross-clamping prompts the spinal cord vasculature to increase CSFP reflexively, lowering SCPP and thereby diminishing blood supply to the spinal cord. Drainage of CSF reduces CSFP, offsetting the gradient and improving SCPP.

In dogs, Kazama and associates found that draining CSF 1 hour into a 2-hour aortic cross-clamping procedure was of limited efficacy. It only increased SCPP by 8–10 mm Hg, not enough to ensure the safety of the spinal cord. Only when CSFP was elevated abnormally (40 mm Hg) did drainage of CSF significantly increase SCBF (from 12 to 17 ml/100 g/min) and prevent damage to the spinal cord. Blaisdell and Cooley found that the incidence of paraplegia associated with aortic cross-clamping in dogs decreased from 50% to 8% when CSF drainage was performed during the operation.

McCullough and associates found that draining CSF before 40 minutes of aortic cross-clamping had elapsed increased SCPP from 22 to 30 mm Hg during
Blood supply of spinal cord

aortic occlusion and that the incidence of paraplegia decreased by 90%.

Elmore and colleagues found that draining CSF before a 1-hour period of aortic cross-clamping had elapsed eliminated paraplegia in dogs, although 44% of the animals were paraparetic after surgery. Bower and associates showed that draining CSF before a 1-hour period of aortic cross-clamping had elapsed improved SCPP (from 13.5 mm Hg without CSF drainage to 21.1 mm Hg) and improved SCBF (from 2.5 ml/100 g/min without CSF drainage to 15.1 ml/100 g/min) in the gray matter of the lumbar spinal cord. Furthermore, reperfusion hyperemia in the lower portions of the spinal cord was not present when CSF was drained (34.1 ml/100 g/min) but was present when CSF was not drained (136.6 ml/100 g/min). Of the 7 dogs undergoing CSF drainage, 57.1% exhibited no neurological deficit and none became paraplegic. Of the 44 dogs not undergoing CSF drainage, 62.5% developed spastic paraplegia and none was neurologically normal. In contrast, when Horn and associates drained CSF in rabbits after inducing an SCI, there was no indication that perfusion of the spinal cord improved. The different outcomes may reflect different methods: complete SCI versus aortic cross-clamping.

Pathophysiology of Spinal Cord Blood Flow After Trauma

Basics of SCI

To address spinal cord injuries and how to minimize their deleterious effects, an understanding of the pathophysiological mechanisms that follow SCI must first be achieved. Two types of zone define the spinal cord after injury. One zone completely lacks vasculature able to perfuse the tissue, whereas the other is capable of capillary perfusion within a week of injury. The zone with vessel-less vasculature often consists of the posterior central gray matter and posterior columns at and below the trauma site. The size and extent of the zones vary, depending on the severity of the trauma.

Microangiograms showing vascular changes over various time frames have been used to construct a fairly consistent postinjury timeline. During compression, the extrinsic arteries (ASA and PSA) remain intact, whereas the arteries within the traumatized region become constricted. Five minutes after injury, muscular venules in the gray matter appear distorted and develop holes. Muscular venules in white matter, however, appear to be unaffected. Hemorrhages emerge from capillaries and venules in the border zone between gray and white matter and in the gray matter itself. In these hemorrhagic areas the vessels do not perfuse blood. Fifteen minutes after injury, there is further leakage from gray matter venules and less than one-third of the gray matter vessels perfuse properly. As a result, hemorrhagic areas in the gray matter continue to grow. Although white matter hemorrhages become more pronounced, the number of functioning vessels increases after 30 minutes. One hour after injury, the hemorrhages in the gray matter coalesce and neurons are clearly damaged. Furthermore, most of the vessels near the gray-white matter border cannot perfuse blood. The larger extrinsic vessels (ASA and PSA), however, continue to remain functional. Four hours after injury, vessel leakage is considerable in both the gray and white matter. The only functional intrinsic vessels are limited to the peripheral half of the white matter. After 24 hours, the central arteries at the site of injury and adjacent areas are markedly displaced, often occluded, and become narrowed. Reports on the state of white matter vessels 24 hours after injury have differed. In rats Sasaki found that hemorrhages originating from ruptured vessels in the dorsal white matter were present. In contrast, Dohrmann et al. found that the white matter vessels in cats were almost restored to normal.

Still, the implications are fairly clear. Gray matter is severely injured soon after injury, while damage in white matter is slower to appear and more likely to recover. The predominance of hemorrhages in gray matter may be the result of its rich capillary network, which is highly susceptible to mechanical stress because of its complex texture. This stress can induce clotting, which decreases or halts blood flow, and causes venous hypertension, which can disrupt vessel walls. Edema, a result of vessel leakage, may increase interstitial fluid pressure, causing vessel closures, and creating a snowball effect. Damage to central arteries and their branches causes hemorrhaging and ischemia in their areas of distribution, which includes the gray matter. The pia mater is a strong membrane. Therefore, the large vessels on the surface of the spinal cord and in the anterior median sulcus are relatively spared from major damage due to mechanical stress. The ASA and PSA possess heavier mesenchymal-supporting investment, and electron microscopic studies suggest that white matter vasculature possesses denser glial packing than vessels of gray matter.

Autoregulation With Injury. Spinal cord injury is associated with marked vasculature changes. To further understand chronic changes as a result of spinal injury, cats with various degrees of SCI (control, mild 200 g/cm; severe, 400 g/cm) were observed over a 14-day period after injury. In cats with mild trauma, SCBF and CO2 responsiveness were not significantly different from those of uninjured cats, although there was a trend toward hypoperemia. In cats with severe spinal cord trauma, the hypoperemia was significantly different from that of uninjured cats on the 11th and 14th days postinjury. In this group, CO2 responsiveness was strikingly impaired (0.03 ml/min/100 g/torr compared with 0.47 ml/min/100 g/torr in the controls). One explanation for this delayed increase in SCBF is that hypotension causes transient ischemia leading to a local decrease in pH, both intra- and extracellularly. The hydrogen ions then act directly on blood vessels, causing vasodilation. Other ions and substances, such as potassium and histamine, could employ a similar mechanism.

Postinjury Relations Among MABP, SCBF, and Spinal Cord Function

To better understand how treatments should address spinal cord trauma, considerable research has been directed toward defining relationships among MABP,
SCBF, SSEPs, and neurological outcomes after injury, both at and around the trauma site.

Guha et al. investigated autoregulation of SCBF at an MABP of 81–180 mm Hg in rats at the site of SCI (T-1) and adjacent to the injured sites. The results confirmed normal autoregulation in the control group. Autoregulation was present in the mildly injured group but differed from that of the control group: SCBF was lower, and the lower limit of autoregulation was increased to 101–120 mm Hg. In contrast, autoregulation was lost at both T-1 and C-6 in the severely injured group.

Various studies have examined the effect of changing MABP after trauma in an attempt to normalize SCBF. Dolan and Tator found that by increasing the MABP in rats after trauma (175-g cord clip-compression for 1 minute), SCBF also increased. Thirty minutes after injury, SCBF in the white and gray matter were a fraction of control values (3.42 from 18.7 ± 6.7 and 15.6 from 74.2 ± 22.2 ml/100 g/min, respectively). After MABP was increased by blood transfusion, SCBF almost doubled in both white (6.3 ± 6.4 ml/100 g/min) and gray (25.6 ± 30.2 ml/100 g/min) matter.

The results of Guha and associates’ study of rats implied that restoring MABP to its baseline after severe injury was the best option when altering MABP. With hypotension, posttraumatic ischemia persisted and worsened, whereas with extreme hypertension (180 mm Hg), SCBF was lower, and the lower limit of autoregulation was increased to 101–120 mm Hg. In contrast, autoregulation was lost at both T-1 and C-6 in the severely injured group.

Lohse and associates found that MABP spiked and then fell below baseline values after light (100 g/cm) and moderate (260 g/cm) trauma in cats. After light trauma, MABP immediately increased to 137% of pretrauma values. After 15 minutes, it decreased to 77% of the pretrauma value and remained low for the 6 hours of the experiment. After moderate trauma, the MABP rose to 144% of its pretrauma value, decreased to 72% of that value, and remained low for the duration of the experiment. Five minutes after severe trauma (300 g/cm) in monkeys, SCBF in the gray matter fell to 62% of baseline, whereas in the white matter it fell to 93% of baseline. After 15 minutes, SCBF in gray and white matter rose (to 92% and 141%, respectively). During the next 45 minutes, SCBF in the gray and white matter again fell (to 21% and 90%, respectively). After this point, SCBF in white matter increased slowly, whereas the SCBF of gray matter did not. These data show that as severity of trauma increases so do fluctuations in SCBF.

Another obvious result of increasing the SCI force is depression of SCBF gray matter. Holtz and associates’ research supports this finding. They showed that post-trauma motor function likewise declines. Griffiths reported similar results using CO₂ sensitivity as a measure.
of neurological dysfunction. After moderate injury (300 g/cm), CO₂ sensitivity was considerably reduced and was nonexistent after severe injury (500 g/cm).

Carlson and associates⁹ addressed the question of reperfusion after injury in dogs and found that duration of spinal cord compression (30, 60, and 180 minutes) and reperfusion after decompression were inversely related. Five minutes after compression, SCBF increased from baseline (21.4 ± 2.2 ml/100 g/min) in both the 30-minute group (49.1 ± 3.1 ml/100 g/min) and 60-minute group (~44 ml/100 g/min) but fell slightly in the 180-minute group (19.8 ± 6.2 ml/100 g/min). Fifteen minutes after compression, the 30- and 60-minute groups remained above baseline (32.3 ± 4 and 32.4 ± 3.7 ml/100 g/min, respectively), whereas SCBF in the 180-minute group did not change significantly. Similar results have been observed in other animals, including pigs and monkeys.⁴,⁵,⁹

These differences in SCBF after trauma have a direct impact on vascular resistance. After trauma, SCBF, vascular resistance, and MABP all depend on one another (SCBF = MABP/vascular resistance). Therefore, when moderate and light trauma decrease MABP and increase SCBF, vascular resistance will decrease. Because severe trauma decreases SCBF, vascular resistance increases.
This is a clear distinction between traumatic injuries that do and do not cause paraplegia. The mechanisms that might mediate such changes in local vascular resistance are unknown, but several possibilities exist. Changes in hydrogen and potassium ions, the release of biologically active substances, or primary injury to the microvasculature could affect vascular resistance.25

Using contrast material to capture extravasation, Allen and associates7 evaluated microangiograms obtained in cats after moderate and severe injury (300 g/cm and 500 g/cm, respectively). Immediately after moderate injury, several small areas of extravasation were present in the central gray matter of the traumatized region. Fifteen minutes after injury, blood flow was markedly reduced in the gray matter arterial network, as were the size and number of the peripheral arteries serving the posterior horns, especially in the posterior columns. Thirty minutes after injury, the appearance of the peripheral arteries began to approach normal and continued to improve. Over time the degree of extravasation in the central gray matter became more pronounced. After severe injury there were more areas of extravasation than after moderate trauma. Leakage again appeared in the gray matter, but there were also areas of extravasation in the gray and white border region. Fifteen minutes after injury, the SCBF of both gray and white matter was reduced markedly. Over time the central gray matter filled with extravasated contrast material as it had after moderate injury. Perfusion of the white matter improved after 1 hour but remained below control values.7 Reed et al.65 found that 90 minutes after severe (500 g/cm) trauma, microangiography showed severe narrowing of vessels in the gray and white matter. After 2 hours, there was almost no filling of the peripheral vessels supplying the white matter. After 3 hours, the entire gray matter was hemorrhagic and there was no blood flow.

Gray to White Injury

Primary damage directly inflicts injury on neurons and axons. Edema, ischemia, and inflammatory responses are common mechanisms that accelerate damage. Ischemia and reperfusion induce the release of inflammatory cytokines, free radicals, and excitatory amino acids.36 Vascular disruption and local tissue ischemia are features of secondary damage.

In the mid 1970s, the prevailing theory concerning the pathophysiology of acute spinal cord injuries relied on 2 steps. First, there was hemorrhage in the central gray matter, which specifically included endothelium separating from the basement membranes, recanalization, blood clotting, and disruption of vessel walls. Ischemia in the lateral white matter followed but included no changes comparable to those in the gray matter. Consequently, gray matter was thought to be the origin of the damage, which slowly spread to the surrounding white matter.4 Wallace and associates86 found that ischemia in the white matter of rats, especially in the dorsal columns and anterior and lateral funiculi, was common when fed by arteries that traversed hemorrhagic gray matter. This finding further supports the secondary nature of injury in the white matter, stemming from trauma to the gray matter.

Kobrine and associates’ experimental study46 investigating the impact of severe (600 g/cm) injury in monkeys opposes this theory. In the lateral white matter SCBF more than doubled (p < 0.01) within 1 hour of injury and returned to normal after 8 hours. In the central gray matter SCBF fell for 4 hours after injury. Cawthon and associates69 reported similar results in cats after severe trauma (500 g/cm). White matter SCBF almost rebounded to baseline values within 8 hours. An hour after trauma, SCBF in the white matter at the trauma site was near control values (10.99 ± 0.89 ml/min/100 g), whereas rostral and caudal blood flow was depressed for approximately 1 cm. Four hours after trauma, blood flow through white matter was depressed at the trauma site. Two centimeters rostral and caudal to the site, blood flow was also depressed to a lesser extent. Eight hours after trauma, blood flow through white matter was 90% that of the controls 3 mm caudal to the trauma center, and 16 mm caudal to the trauma center it was 97%.10

These findings suggest that the initial trauma disrupts the ability of the white matter to function and that injury is not simply a result of spreading from gray to white matter. These data show that autoregulation in white matter is maintained through the 1st hour after injury and then lost. The reappearance of normal blood flow 5–7 hours later indicates that autoregulation is regained. The return of blood flow may depend on clearing the tissue of toxins, vasospasm, or other mechanisms that restore vasoconstriction.39 The increase in SCBF in white matter after injury also could be a response to increased metabolic demand or loss of autoregulation and subsequent vascular dilation as a direct result of trauma.46 A documented increase in histamine levels at the site of trauma, known to cause vascular dilation by weakening vascular tone, also explains the increased blood flow in white matter.57

Segmental loss of gray matter is functionally tolerated because it involves only a small portion of the total neuronal pool in gray matter. Loss of segmental white matter, however, is more serious because all distal functioning neurons cannot operate and neurological deficit occurs. If treatment could be initiated before white matter is destroyed (within 3–4 hours of severe injury), paralysis might be avoided in some cases.25

White Matter Issues

The severity of trauma within white and gray matter varies but is greatest in the white matter. Understanding how specific areas of the spinal cord react to traumatic injury clarifies the ability of the vasculature to function. Sandler and Tator67 found that after moderate trauma was induced in monkeys by inflating an extradural cuff to 400 mm Hg for 5 minutes, the SCBF in the dorsal columns and dorsolateral white matter rebounded slower than in other areas of the white matter. In the lateral ventral areas, SCBF was significantly different from that of the controls for 30 minutes after trauma, but the SCBF in the dorsal columns and in the left lateral dorsal white matter was still significantly lower after 6 hours compared with controls. After 24 hours, blood flow in all of the white matter was significantly higher than in the controls.
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Conclusions

Spinal cord vasculature has unique anatomical and physiological properties. Variability in the direction of blood flow and in the diameter of arteries ensures a constant and sufficient blood supply, but there are regions of the spinal cord that can be readily made ischemic. The pathophysiology of SCBF under normal conditions has been investigated, and it seems that consensus has been reached on the key mechanisms of the blood supply to the normal spinal cord. Although numerous experiments have attempted to investigate the principles elucidating the blood supply in the injured spinal cord, these mechanisms remain unclear. Techniques that would allow continuous precise measurement of blood flow in different spinal cord regions could potentially answer many of the questions regarding how the blood flow is altered. Further optimization of Doppler ultrasonography and arterial spin labeling MR imaging could potentially meet these requirements. Manipulating physiological parameters such as MABP and intrathecal pressure may have potential in improving the blood supply to ischemic areas of the injured spinal cord.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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Address correspondence to: Nicholas Theodore, M.D., Neuroscience Publications, Barrow Neurological Institute, 350 West Thomas Road, Phoenix, Arizona 85013. email: neuropub@chw.edu.