NIKOLA ILIĆ

ISCHEMIA OF THE SPINAL CORD IN AORTIC SURGERY
Nikola Ilić
Department of Surgery, Faculty of Medicine, University of Belgrade, Serbia
Clinic for Vascular and Endovascular Surgery, Serbian Clinical Centre, Belgrade, Serbia

Reviewers
Prof. Dr. Živan Maksimovic, vascular surgeon
Prof. Mile Vraneš, cardiac surgeon
Doc. Dr. Vladan Popović, vascular surgeon

Acknowledgments
I would like to thank Milica Knezevic for translation, revision and editing this text.

Presented study is a part of a scientific research project (grant No 175008) supported by the Ministry of Education and Science of the Republic of Serbia.
To my teacher of vascular surgery,
Professor Dr. Lazar Davidović,
for the inexhaustible inspiration and motivation
and to my family, whose love and support made
all this possible and worthwhile.
When Adamkiewicz in 1881 published a paper in which he showed the role of *arteria radicularis magna* (which was later named after him) in the vascularization of the spinal cord, he had no idea of how high the importance his discovery would have for the surgery of thoracic and thoracic-abdominal aorta, which followed nearly two centuries later. In his experimental works from the beginning of XX century, Carrel showed that the prolonged clamping of the thoracic aorta causes paraplegia due to irreversible ischemic damage to the spinal cord. Even if it does not lead to death, its importance is enormous since it usually causes permanent disability or paraplegia. Surgeons faced this problem in practice in the 1950s when this surgery started being applied. De Bakey and Cooley in 1953 were the first to treat surgically aneurysm of descending thoracic aorta. The clamping during that procedure was 45 minutes long. Although no protective measures were employed, the patient did not have any signs of ischemic damage to the spinal cord. As the number of these surgeries grew, some were followed by the spinal cord ischemia. Why? In 1989 Kiefer divided the aneurisms of thoracic-abdominal artery into four different groups based on the point of departure of Adamkiewicz artery: those that are above it, those from which the aorta starts from, those below it and those which cannot have the point of departure clearly determined. If in the first two cases no protection is employed, while the clamping is longer than 30 to 45 minutes, paraplegia will occur. De Bakey and Cooley’s patient was probably lucky because the clamping was below 45 minutes. When he described that procedure to Viking Bjorck, De Bakey said: “You know, we didn’t know that there had been risk of the spinal cord ischemia then. We only learned that later”.

Development of the thoracic-abdominal aorta surgery was greatly governed by the introduction of new methods, whose aim was better prevention of ischemic damage to the spinal cord. Retrograde perfusion was not enough, since there are periods when it is not applicable. Therefore, the following innovations were very significant: cerebrospinal liquor drainage – Hollier in 1988; identification of the point of departure of Adamkiewicz artery – Kiefer in 1989; indirect determination of the flow necessary for the functioning of motor neurons of the spinal cord by recording the MEP – Jacobs. During the last two decades, new theories of the spinal cord vascularization have occurred, giving different importance to Adamkiewicz artery. Surely, the most important is the one based on the collateral network concept. The monograph by Dr. Nikola Ilić describes in
detail the spinal cord vascularization, pathophysiology of the spinal flow, etiology of the spinal ischemia, or the protection measures, the purpose of which is to prevent the ischemia of thoracic-abdominal aorta during surgical procedures. There is not a book today, which describes in such a detail and in one place, all the aspects of this problem. That is one of the many reasons why this one is unique. Without previously listed findings, surgical treatment of thoracic and thoracic-abdominal aorta aneurysm cannot be imagined today. According to many experts, open surgical treatment of thoracic-abdominal aorta aneurysm is technically and technologically the most demanding vascular surgical and anesthesiology procedure. It can be performed only by highly specialized, expert, multidisciplinary teams in institutions with significant resources and work scope (so called high volume centers). Dr. Nikola Ilić has important place in one such team at the Department of Vascular and Endovascular Surgery, Clinical Center of Serbia, the only in the region that routinely deals with these procedures. Therefore, this monograph is at the same time the result of the thorough analysis of the latest literature, experience of the Clinic at which Dr. Nikola Ilić works and his personal experience. I believe that in addition to the local experts that are interested in this problem, the monograph will find readers worldwide as well.

Prof. Dr. Lazar Davidović,
Professor of Surgery, Faculty of Medicine, University of Belgrade,
Head of Clinic for Vascular and Endovascular surgery, Clinical Centre of Serbia, Belgrade
Spinal cord ischemia remains the most impressive and colliding complication following open surgical and endovascular aortic procedures. Paraparesis and paraplegia are devastating, having a major invalidating impact on the patient’s life. Also for the surgeon and the entire team this dramatic adverse event causes a significant concussion. During the last decades, extensive research has been focused on discovering the mechanisms leading to spinal cord ischemia. Several adjunctive measures have been developed to reduce the incidence of neurological deficits, however, its occurrence remains critical. The main reason for this unsolved problem is the complexity and multifactorial pathophysiology of spinal cord ischemia. First, the anatomy of the spinal cord blood supply does not always correlate with the function of the grey and white matter. Second, peri-operative alterations in blood pressure, cerebro spinal fluid pressure, pharmacological interventions, temperature changes, embolic processes, steal phenomenon’s, capillary edema and many other mechanisms are all interacting during one and the same surgical procedure. Accurate assessment of all these cross firing factors on-line is not feasible, therefore limiting adequate interventions and therapeutic strategies. Dr. Nikola Ilić has compiled all available knowledge, information, research and clinical data on spinal cord ischemia after aortic surgery. Following historical reflections he describes the classical anatomy theory, originally addressed by Adamkiewicz. The differences between acute and delayed paraplegia have extensively been explained, including the different strategies to minimize cord ischemia. Dr. Ilić also described the techniques to assess spinal cord integrity, preconditioning and the approaches to increase and develop collateral pathways. Finally, he discussed the experience after endovascular treatment of descending and thoraco-abdominal aortic aneurysms as well as measures to reduce the incidence of spinal cord ischemia. This book is a comprehensive overview on spinal cord ischemia following aortic procedures and helps in understanding the complexity of the puzzle. It also motivates to continue basic and clinical research in the battle against this terrible medical complication. I can recommend reading this beautiful work to everybody involved in this specific part of medicine.

Prof. Dr. Michael Jacobs
Chairman and Professor of Surgery, Department of Surgery
Executive Director Heart + Vascular Center,
Maastricht University Medical Center, The Netherlands
## Contents

**FOREWORD** ........................................................................................................ VII

**PREFACE** ........................................................................................................ IX

**VASCULARIZATION OF THE SPINAL CORD** ........................................... 1
  - Classical anatomical theory ............................................................................... 1
  - Concept of collateral network ......................................................................... 6
  - Biglioli’s theory ............................................................................................... 9

**PATHOPHYSIOLOGY OF BLOOD FLOW THROUGH THE SPINAL CORD** ........ 10
  - Physiology of blood flow .............................................................................. 10
  - Watershed zone concept .............................................................................. 10
  - Pathology of the spinal cord infarct .............................................................. 11
  - Aortic cross clamp ......................................................................................... 12
  - Blood pressure ............................................................................................. 13
  - Pressure of the cerebrospinal fluid ............................................................... 13
  - Steal phenomenon ....................................................................................... 14

**PRESURGICAL ASSESSMENT OF THE SPINAL CORD VASCULARIZATION** .... 16
  - Angiographic assessment of intercostal arteries .......................................... 16
  - CT angiography ............................................................................................. 17
  - MR angiography ........................................................................................... 18

**ETIOLOGY OF SPINAL CORD ISCHEMIA** .................................................. 21
  - Initial experimental studies .......................................................................... 21
  - Acute paraplegia ........................................................................................... 22
  - Delayed paraplegia ........................................................................................ 23
Vascularization of the spinal cord is extremely complex and variable. Conditions such as aneurysmatic aorta and dissection greatly contribute to the complexity of vascularization, and consequently complicate the diagnosis of the disease and surgical treatment of patients. In recent decades resection of thoracic-abdominal aneurysms has become an inevitable surgical discipline, which therefore imposed better understanding of anatomy and physiology. Interest in the spinal cord vascularization dates about 130 years back, thanks to the Polish pathologist Albert Wojciech Adamkiewicz¹ and his monograph, which was first to describe a large branch in the lower thoracic or upper abdominal parts, today known as Adamkiewicz artery (Figure 1). In 1970s Lazarothes et al.,² with a series of dissections and angiographies clarified anatomical appearance and contribution of Adamkiewicz artery to vascularization of the spinal cord. However, in the last two decades, new theories and concepts of understanding vascularization appear, that shed new light on this issue. Three concepts dominate:

- classical anatomical (Adamkiewicz) theory;
- collateral network concept, and
- Bigliolo’s theory.

### CLASSICAL ANATOMICAL THEORY

#### Outer arterial system

##### Segmental arteries

Spinal cord, para-spinal muscles, dura and nerve roots are supplied with blood from the segmental arteries. Vascularization of the cervical part of the spinal cord is subject to change.
and is usually derived from the vertebral artery and costo-cervical and tireo-cervical trunk, and partly from the ascending pharyngeal and occipital artery. Above the third thoracic vertebra several segmental arteries have common point of departure, and such segmental artery is called a. intercostal suprema. This artery may also be a branch of costo-cervical trunk, aortic arch or vertebral artery. It supplies blood to the upper thoracic segment and part of the cervical segment. Segmental arteries in the thoracic and upper lumbar part come out in pairs from the posterior segment of the descending aorta. In the thoracic part there are nine pairs of segmental arteries (a. intercostales posteriores) and a pair of subcostal arteries, while the lumbar region has four pairs of lumbar segmental arteries which come out of the descending aorta and correspond to the position of the third and fourth lumbar vertebra. Below the third thoracic vertebra, one pair of segmental arteries is located at each level, supplying blood to the dorsolateral tissue but not to the spinal cord. At each level between segmental arteries there are rich anastomoses.

Segmental arteries on the left side exit from the posterior segment of the aorta in the thoracic and lumbar region, while the segmental arteries on the right side start in the medial part of the aorta in the top thoracic region, and in the lumbar region out of the posterior part of the aorta (Figure 2). Segmental arteries from the upper thoracic region start out from two caudal vertebrae from the level they supply blood to, so they have cranial course. In the lower thoracic and upper lumbar segments arteries start immediately below their respective vertebrae, and they have shorter cranial course. In the lower lumbar region the exits of segmental arteries are localized in the central area of the third and fourth lumbar vertebra.³

It is important to realize that the segmental arteries are named according to the level of spinal cord that they supply, and not according to the level of the spinal column from which they originate. Each segmental artery in the thoracic section can be named according to the corresponding rib. Segmental arteries from the lower lumbar and sacral sections are branches of hypo-gastric artery and branches of a. sacralis media, which comes out of the aortic bifurcation. In some patients, in the vascularization of the conical segment of the spinal cord between the second and fifth lumbar vertebrae (L2 and L5) participates conical artery or Desproges-Gotteron artery, a branch of the internal iliac artery.⁴

**Radicular arteries**

A segmental artery is divided into anterior and posterior branch soon after its point of origin. The posterior branch divides into spinal

---

**Figure 2.**
Exterior vascularization of the spinal cord: 1) basilar artery; 2) vertebral artery; 3) anterior spinal artery; 4) posterior spinal artery; 5) anterior radiculo-medullar artery; 6) ascending cervical artery; 7) deep jugular artery; 8) subclavian artery; 9) posterior radiculo-medullar artery; 10) segmental arteries; 11) Adamkiewicz artery; 12) lumbar arteries; 13) sacral branches.
artery and lateral and medial muscle-cutaneous branches. Spinal artery of each segmental artery enters the spinal canal at the level of the intervertebral foramen and divides into: retro-corporal arteries, which supply blood to the vertebrae, ligaments and to a certain extent the dura mater, and radicular arteries, which supply blood to the dura and nerve roots at each level, but not necessarily to the spinal cord. They are called radicular-meningeal arteries, and are located on each vertebral level. However, radicular arteries provide branches for vascularization of the spinal cord only on the several levels. These branches are called radicular-medullar arteries (Figure 3). They are divided into anterior and posterior radicular-medullar arteries, depending on whether they supply blood to the front or rear spinal artery. In average, there are six anterior radicular-medullar arteries, while there are between 11 and 16 posterior radicular-medullar arteries. In the cervical region, there are two or three radicular-medullar arteries that branch into the typical Y or T shape. In the thoracic segment

Figure 3.
Model of Adamkiewicz artery (arteria radicularis magna): A) arteria radicularis magna; B) branching of arteria radicularis magna; C) smaller ascending branch; D) typical form resembling a hairpin; E) larger descending branch. NM=neuro-medullar artery; RA=anterior radicular artery; RP=posterior radicular artery. (From: Melissano G, Civilini E, Bertoglio L, Callieri F, Campos Moraes Amato A, Chiesa R. Angio-CT imaging of the spinal cord vascularisation: a pictorial essay. Eur J Vasc Endovasc Surg 2010;39:436-40).

Figure 4.
Percentage of distribution of points of origin of ARM by spinal segments.

Figure 5.
Pathological sample of the spinal cord with a corresponding schema which clearly shows the separation of AMR in the shape of a hairpin (arrow). ASA=anterior spinal artery; Med=medulla.
there are usually one or two radicular-medullar arteries, whereas in the lumbar region there is generally only one. This most important radicular-medullar is arteria radicularis magna (ARM) or Adamkiewicz artery.

ARM enters the vertebral canal at the level between the ninth and twelfth thoracic vertebra (Th9 and Th12) in 75-78% of cases \(^7,8\) and has a diameter of 0.5-1 mm (Figure 4). \(^6\) The most commonly, it starts from the lowest left intercostal artery and under a curved angle (which resembles a hairpin) flows into the anterior spinal artery (Figure 5). If ARM starts from the lumbar artery, then there is usually another artery in the middle thoracic region.

**Internal arterial system**

**Anterior spinal artery**

Anterior spinal artery originates at the level of the foramen magnum by merger of descending branches of the intracranial segment of the vertebral arteries. One of these branches is often dominant. Descending branches can be connected in level between the second and fourth vertebrae (C2-C4), or one of these two branches, usually a smaller in diameter, can blindly end as a centrally localized artery (Figure 7). \(^6\)

Anterior spinal artery extends along the anterior sulcus of the spinal cord, it is continuous and continued caudally to yield less important branch of the *filum terminale*, and surrounds the cone, providing numerous anastomoses.
through *rami cruciantes* with the posterior spinal arteries (Figure 8). Although its diameter varies (0.2-0.8 mm), it is the thinnest in the thoracic and widest in the conic region. On her way, the anterior spinal artery is supplied with blood by inflow from the radicular-medullar arteries, in order to ensure proper flow through the spinal cord. The flow through the anterior spinal artery is provided from four major regions: cervical, thoracic, lumbar and sacral. It supplies blood to the anterior two thirds of the spinal cord through central and pial branches, including the anterior horns, spinal-thalamic and corticospinal tract.

The main inflow for it is provided in the segment between C4 and C8. There are also a number of secondary tributaries to the anterior spinal artery coming out of the vertebral arteries. These branches are usually small, except for one in the proximity of C3, which is easy to detect in angiography because of its size. Other tributaries originate from costo-cervical tree, thyro-cervical trunk and the ascending cervical artery. They usually provide branches for segment C4-C6, while the deep cervical artery supplies C7 and C8.\(^{12}\) Front spinal artery branches out providing vascularization of the parenchyma of the medulla, which is divided into central (centrifugal) and peripheral (centripetal). The central system consists of the central artery, which branches off from the anterior spinal artery, and enters the front fissure median, branching out in the form of a tree in gray mass (Figure 9). Peripheral system consists of small perforating branches which exit out of pial plexus, branch out in the white mass and supply blood to the periphery of the medulla.

### Posterior spinal arteries

Two posterior spinal arteries originate at the level of the foramen magnum from the branches of the ipsilateral vertebral artery or from posterior bottom cerebellar artery. They extend along the right and left posterior-lateral surface of the spinal cord and receive corresponding posterior radicular-medullar arteries at all levels. The system of posterior arteries is often discontinuous and arteries sometimes cross to the opposite side of the spinal cord to ensure adequate vascularization. Usually 11-16 radicular-medullar arteries contribute to vascularization of posterior spinal arteries, with the largest posterior radicular-medullar artery entering the posterior spinal arteries at the level below the inflow of ARM. Posterior spinal arteries supply blood to the posterior aspects of medulla, the dorsal gray matter, as well as surface and lateral segments of spinal cord.

### Pial plexus

In addition to the significant anastomotic network between the anterior and posterior spinal arteries, at the level of the cone of the spinal cord, such anastomotic network exists along the entire surface of the medulla. This network is known as pial plexus or vasa corona, and it consists of slant and transverse branches that supply the peripheral segment of the medulla.
Internal venous system

Veins of the anterior medial group (central veins) collect blood from both medial segments of the anterior horns, anterior gray commissure and white mass of the anterior funiculus. They also drain adjacent segments above and below the inter-segmental anastomosis. They merge with other veins within the fissure. At the end, the central vein pours in the front median spinal vein. Other groups consist of veins originating from the capillary network near the periphery of the gray or white mass. They are oriented radially and directed outwardly, toward surface of the medulla, where they merge with the surface plexus of veins around medulla forming the vasa corona or corona plexus. These veins are mostly situated in the white mass of the posterior and lateral funicular, but they can also be found in anterior funiculus. Radial veins dominate cervical and thoracic segment and drain blood laterally from the gray mass of external horns.

External venous system

External venous system is less developed in the posterior segments of medulla, whereas it is substantially developed in the lumbosacral region. There are rich anastomotic networks between major venous trees. Posterior spinal vein descends in the region of the posterior medial septum. This vein drains blood from the posterior segments of the white mass and posterior horns. Anterior spinal vein follows the anterior spinal artery and receives sulcus veins. Anterior and posterior spinal veins drain in the radicular veins, which extend along the anterior and posterior spinal roots. These radicular veins end in paravertebral and intervertebral plexus and then in azygous vein and pelvic venous system. The absence of valves in the venous system allows for greater susceptibility of spinal veins on application of Valsalva’s maneuver and increased intra-abdominal pressure (Figure 10).

CONCEPT OF COLLATERAL NETWORK

Collateral network concept is employed in the past twenty years as a result of a variety of laboratory and clinical studies of Griep and Griep, 13, 14 The basis of this concept is the axial
collateral network of small arteries of the spinal canal, prevertebral tissue and para-spinal muscles, which is anastomosed both to each other, and to the nutritive arteries of the spinal cord (Figure 11).

The pressure in this network is about 75% of the mean arterial pressure (MAP) and hence is liable to critical changes according to the rise of central venous pressure (CVP) or fall of the perfusion pressure (Figure 12). Reduction in the value of collateral pressure is directly proportional to the number of sacrificed segmental arteries. It takes mostly five days after the surgery to recover the value of collateral pressure. It was also shown, when the segmental arteries were sacrificed in two acts, that the reduction of collateral pressure is substantially less, and that time necessary for its recovery is significantly shorter. Distended epidural veins, fixed in the spinal canal, after an increase in CVP may physically compress arterioles and reduce perfusion pressure through the collateral network. The so-called inflow into this collateral network does not consist of only segmental blood vessels, but also of subclavian artery and hypo-gastric artery with its terminal branches. In this way, collateral network can provide sufficient flow from a single source if the flow rate at the other source is decreased. Griep and Griep studies corroborate the idea that the circulation of the spinal cord is continuous and flexible system in the way that the inflow from any of the segmental arteries is unlikely critical. Further studies have shown that the total number of sacrificed segmental arteries during surgical reconstruction of thoracic-abdominal aorta is more specific.
indicator of risk of paraplegia than the loss of any segmental artery. Experimental animal studies have revealed that after sacrificing the segmental arteries, a remodeling of inter-spinal arteries and collateral network commences. Remodeling mechanism probably occurs as a consequence of two factors: stimulus of developing of capillary network due to hypoxia (angiogenesis) and the change in hemodynamics of flow and of local mechanical factors (arterio-genesis). After de-clamping of aorta, flow through the collateral network increases eight times in 20 minutes. Over next 24 hours dilation of collateral network starts, but the entire remodeling takes about five days. Basis for the remodeling is the increase of the density and diameter of arterioles, both in the epidural para-spinal network and in the para-spinal muscles. Interestingly enough, the diameter of the arterioles is increased only five days after the ligature of segmental arteries, while the diameter of the anterior spinal artery is increased in 24 hours. At the same time there is a parallelism of para-spinal blood vessels along the spinal cord and the increase in the diameter of the front spinal artery (80-100%) in the cranial or caudal direction, i.e. in the section which will provide the best perfusion of spinal cord ischemia. Parallelization phenomenon most likely enables better supply of para-spinal muscles, but also in view of the interconnectedness of inter-spinal and para-spinal blood vessels at each level, it is possible that in this way, the flow can be focused in both directions to or from (steal) the spinal cord (Figure 13). The real role of this phenomenon has yet to be explored. Jacobs et al. support the concept of collateral network and point out that ARM is irrelevant, and that it probably does not exist in most people with thoracic-abdominal aneurysms. As an extreme example of collateral network of extra segmental character they give 8% of patients with type II and III of thoracic-abdominal aneurysms who did not have one pervious segmental blood vessel, while the motor evoked potentials (MEP) remained unchanged until

Figure 13. Parallelization process of small blood vessels in para-spinal network 24 hours and 120 hours after the ligation of the segmental arteries in pigs: A) native network with pervious segmental arteries; B) 24 hours after the occlusion of the segmental arteries; C) five days after occlusion of segmental arteries (Etz CD et al.).
the time of clamping of iliac arteries. From this point it appears that routine sacrifice of all intercostal and lumbar arteries may be possible without ischemic lesions of the spinal cord. This is particularly important for achieving the full potential of endovascular treatment of thoracic and thoracic-abdominal aorta.

**BIGLIOLI’S THEORY**

Biglioli et al. performed anatomical dissection of the spinal cord on cadavers using methylene blue stain for perfusion of both vertebral arteries. In contrast to classical theories and findings by Gharagozloo et al., they found the front spinal artery without interruption of continuity. The source of ARM was between T9 and L5, but most usually between T12 and L3—in 83.9% of examined. Departure from the left side was recorded at 67.7% of examined. If the front spinal artery is not continuous, the technique of distal perfusion can be justified. On the other hand, if the front spinal artery has continuity, then it can provide a flow for thoracolumbar segment from the vertebral and cervical arteries even if all intercostal arteries were closed. This would enable the prevention of so-called steal phenomenon from the anterior spinal artery through radicular-medullar artery distal to the clamp position which can lead to ischemic lesion of the anterior two-thirds of the spinal cord, including the motor zone. Given the variability of the ARM points of origin, two thirds of which originate from the lumbar artery, re-implantation of intercostal arteries would not make sense in reduction of the incidence of paraplegia. On the contrary, it would contribute to the increase in neurological deficit due to prolonged clamping of the aorta. The drawback of this study is certainly the absence of aneurysmal disease in a cadaver, as well as the static (and not the dynamic) assessment of the flow through the spinal artery. Biglioli’s technique of fast clamping is based on the principle of this theory.