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Vascular Anatomy of the Spinal Cord

Neuroradiological Investigations and Clinical Syndromes

With collaboration of Ch. Rossberg and A. Mironov

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Armin K. Thron, M.D.
Professor of Neuroradiology
Department of Neuroradiology, University of Tübingen, Federal Republic of Germany

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Preface

The idea for this treatise on the radiological anatomy of superficial and deep spinal cord vasculature evolved from daily routine neuroradiological work. This was also the reason for subdividing the monograph into a postmortem anatomical and a clinical part.

The actual importance of a clear conception of radioanatomic fundamentals was made clear by many clinical conferences with neurologists, neurosurgeons and orthopedists, where a lack of knowledge about medullary syndromes of suspected vascular origin became evident. Also among neuroradiologists there is still widespread uncertainty in the interpretation of myelograms and angiographies in such cases. A study of the spinal cord's angioarchitecture is all the more justified and necessary considering the vast number of descriptions of cerebrovascular anatomy and pathology.

The clinical challenge posed by patients suffering from partial or complete transverse spinal lesions has grown due to new diagnostic and therapeutic approaches. Myelography using water-soluble contrast media, X-ray computed tomography, magnetic resonance imaging and spinal angiography today allow and require both earlier and topographically and pathogenetically more exact classification of diseases of the spinal cord and its surrounding structures. Due to progress in microneurosurgery and interventional neuroradiology, even intramedullary lesions have become more and more accessible and treatable. Therefore this monograph mainly addresses those concerned with invasive therapeutic techniques and who are familiar with the interpretation of radioanatomic findings.

A comprehensive description of medullary vascular syndromes would be beyond the scope of this treatise. Much more physiological and pathophysiological data will have to be collected for this to be possibly accomplished in the future.

Our present diagnostic standard is illustrated by the neuroradiological studies in patients with spinal vascular malformations. The primary intent of this book, however, is a contribution to the widely unknown anatomy of the medullary venous system. Many angiographical findings indicate an important pathogenetic role of the spinal drainage system. Further clarification of these hemodynamic problems will require even more interdisciplinary cooperation among physiologists, neurologists, neuroradiologists, neurosurgeons and neuropathologists.

Aachen, January 1988 **Armin K. Thron**

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These studies were performed at the Department of Neuroradiology, University of Tübingen, and it is to the Department's head, Prof. Dr. K. Voigt, that I express my gratitude for constant support.

Comprehensive postmortem and clinical investigations are impossible without the assistance of colleagues. In the first place I would like to thank Dr. Ch. Roßberg from the Neuropathological Department at the University of Marburg for removing and preparing the postmortem specimens. Without her assistance, the study could not have been realized. Furthermore, I owe thanks to my colleague Dr. A. Mironov for his help in postmortem preparations. Valuable support was also lent by Prof. Dr. J. Peiffer, Institute for Brain Research at the University of Tübingen and by his collaborators who kindly provided their laboratory facilities as well as by Prof. Dr. Dauber, who made the initial anatomical studies possible.

Dr. Poremba provided the instructive schematic drawings of figures 2–5. Special thanks are further expressed to Mr. Wiehr for wonderful photographic work and his keen interest as well as to Mrs. Virginia Müller and Dr. H. Steinmetz for the translation.

Furthermore, I would like to thank Prof. Dr. J. J. Merland (Hôpital Lariboisiere, Paris) and Prof. Dr. B. Kendall (National Hospital, Queens Square, London) for the inspiration gained through their work and personal contact.

Contents

I. Introduction

The relative inaccessibility of the medulla within the spinal column constitutes a major obstacle for both in vivo and postmortem studies. This fact as well as the complex and highly variable blood supply of the spinal cord explain why our knowledge about the physiology and pathophysiology of medullary circulation is still limited. As late as 1958, Gillilan mentions that knowledge of the spinal vascular supply was apparently so deficient among neurologists and neurosurgeons that clinical studies almost always began with a synopsis of the normal medullary blood supply. Clinical syndromes such as the anterior spinal artery syndrome, intermittent spinal claudication (Verbiest, 1954, 1976, Jellinger and Neumayer, 1972) and the vascular myelopathies (Neumayer, 1967) are largely unexplained with regard to their pathogenesis. From our present morphological knowledge we cannot understand the course taken by the repeatedly reported fibrocartilaginous emboli of intervertebral disk tissue into the anterior spinal artery (Peiffer et al. 1976). Until recently, the subacute necrotizing myelitis (Foix-Alajouanine disease), later termed "angiodysgenetic necrotizing myelopathy" (Scholz and Manuelidis, 1950), was considered a distinct clinical entity, and only lately could its underlying vessel anomaly be satisfactorily demonstrated and interpreted. Disorders whose pathogenesis also involves vascular mechanisms, such as the syndromes of the narrow spinal canal or of slowly progressive tumor compression, were usually explained in the past by decreasing arterial supply. Despite the well-known pathoanatomical fact that arteriosclerosis of the medullary vessels is extremely rare, literature on spinal circulatory disorders abounds in explanations analogous to the conditions in ischemic brain disease, where obstructions in the arterial vasculature are often found. This becomes understandable in light of the fact that even today the possible impact of venous disorders cannot be clinically estimated, although circulatory deficiencies in the venous system have occasionally received pathoanatomical and surgical attention (Stochdorph, 1961, 1969; Jellinger, 1966; Neumayer, 1966; Wüllenweber, 1969).

The anatomy of the spinal vessels forms the basis for our understanding of primary or secondary spinal cord circulatory disorders. Standard handbooks usually display this anatomy only schematically. The lack of direct reproductions, controversial findings due to interindividual variations of spinal vessels, and the present inability of in vivo angiography to describe the entire spinal circulation, all these inadequacies led to an encompassing radiological study of the spinal vascular system in postmortem specimens.

This radioanatomical work, supplemented by comparative studies of medullary lesions forms the first part of this book:
It provides a systematical, three-dimensional reproduction of the superficial and intrinsic spinal arteries and veins using microradiographical techniques.

The clinical problems outlined above have gained actuality through progress in neurophysiological diagnostics, microneurosurgical techniques and especially through the new neuroradiological methods of examination. Selective spinal angiography, developed since the sixties, myelography using watersoluble contrast media and magnetic resonance imaging (MRI) have all expanded the diagnostic capabilities in spinal processes.

The second, clinical section of this book is devoted to these diagnostic improvements with emphasis on spinal arteriovenous malformations (AVM). This clinical work as well as pathomorphological and pathophysiological considerations must be regarded as only the present state of knowledge in a rapidly developing field of diagnostic potentials and therapeutic possibilities of interventional neuroradiology.

II. Previous Studies on the Spinal Vascular System

Our limited knowledge about the physiology and pathology of the spinal blood supply contrasts with anatomical descriptions of the spinal vascular system from as early as the end of the 19th century by Adamkiewicz (1881, 1882) and, with a precision that has hardly been achieved since then, by Kadyi (1889). Earlier studies, such as those by Duret (1873) and Ross (1880) were less defined, incomplete and unsystematic. Until about the middle of this century, the spinal vascular system was seldom the object of thorough anatomical research. However, one must mention the comprehensive works of Tureen (1938), Suh and Alexander (1939) as well as Herren and Alexander (1939), who called back to mind the results of Kadyi (1889).

According to these previous investigations the spinal cord is supplied by one ventral and two dorsal arterial anastomotic truncs. They are supplied at the cranial end by feeders from the distal segment of the vertebral arteries, as well as by a varying number of lateral feeders of different caliber entering with the nerve roots at different levels. These radicular feeding arteries originate from segmental arteries or homologous vessels. On the basis of this anatomical knowledge, Bolton (1939) carried out injection studies to examine blood flow direction and vascularization territories of the medulla. As of 1950, the interest in problems of spinal vascular supply was stimulated by progress and questions newly raised by clinical work. Some examples of these are neurological complications following surgery of the aorta and spinal column (Adams and Van Geertruyden, 1956; Hogan and Romanul, 1966; Adams, 1984), neurological syndromes of assumed vascular origin (Kalm, 1953; Zülch, 1954, 1974; Gruner and Lapresle, 1962), and the spinal vascular malformations that had become diagnosable with the introduction of intravital spinal angiography (Djindjian et al., 1963, 1970; Di Chiro et al., 1967; Doppmann et al., 1969). These clinical challenges have since then led to an expansion and deepening of our knowledge. Noteworthy are the studies of Gillilan (1958, 1970), of Lazorthes and co-workers (1958 to 1973), Noeske (1958), Roll (1958), Perese and Fracasso (1959), Clemens and v. Quast (1960), Corbin (1961), Houdart et al. (1965), Romanes (1965), Hassler (1966), Jellinger (1966, 1972), Mannen (1966), Turnbull et al. (1966), Fazio and Agnoli (1970), Manelfe et al. (1972), Piscol (1972), Domisse (1975), Tveten (1976), Crock and Yoshizawa (1977), Crock et al. (1986). Except for a few authors such as Kadyi (1889), Suh and Alexander (1939), Clemens and v. Quast (1961), or Crock and Yoshizawa (1977), the arterial system was more extensively, if not exclusively, examined. Venous anatomy was focussed upon in the studies of v. Quast (1961) as well as Gillilan (1970). The vertebral venous system, connected to the veins of the medulla, was demonstrated quite early by Breschet (1828 to 1832) and later by Batson (1957) and Clemens (1961).

Comparative animal experiments were conducted mainly by Woollam and Millem (1955), Gouaze et al. (1964), Jellinger (1966 a and b) and Tveten (1976).

III. Experimental Methods and Clinical Examination Techniques

1. Anatomical Methods and Materials

Anatomical investigative techniques for the spinal vascular system are based upon preparations using macroscopic-microscopic inspection, histological serial sections and numerous methods of vascular injection. The latter are especially valuable for demonstrating continuous vessel courses. In addition to non-hardening staining fluids such as ink, usually mixed with gelatin (Bolton, 1939; Herren and Alexander, 1939; Suh and Alexander, 1939; Gillilan, 1958; Corbin, 1961; Vuia and Alexaniu, 1969), many hardening substances were used as well. Adamkiewicz (1881) and Kaydi (1889) injected stained glutin and a Teichmann cement of chalk and linseed oil. Other notable substances are PANSCH-mass (Noeske, 1958; Roll, 1958), celloidin (Bolton, 1939), latex solution (Gillilan, 1958; Clemens, 1961; Jellinger, 1966a; Domisse, 1975) or neoprene latex solution (Perese and Fracasso, 1959), synthetic resin (Lazorthes, 1958; Corbin, 1961) or polymerized plastics such as plastoid (Gillilan, 1958; Piscol, 1972). These and other substances which harden out well facilitate corrosive preparations after maceration in potassium hydroxide solution.

Not all substances are equally good for filling both large and small vessels and may easily cause extravasation. Therefore, different methods were often applied separately, especially if visualization of the outer and inner medullary vessels was intended. For the study of vessels within the parenchyma, Adamkiewicz (1881) and Kaydi (1889) used a clearing method with clove oil, mentioned by Virchow (1857). This technique, further developed by Spalteholz (1914), renders tissue sections transparent, so that the stained vessels can be pursued over a certain length under the microscope by turning the knurled screw.

Even without vascular injection, the superficial medullary vessels of the exposed spinal cord can be studied both macroscopically and with a microscope. This is easy with veins of large caliber (v. Quast, 1961), but can also be applied to the determination of radicular feeders and the course and caliber of the ventral and dorsal spinal arteries (Jellinger, 1966a; Mannen, 1966).

2. Injection Techniques

As feeding and draining vessels of the medulla originate from various vascular territories, particular problems are encountered in injection techniques. No method exists as of yet which is qualitatively suitable for a complete demonstration of both the extra- and intraspinal vessels.

In principle, the most appropriate technique is considered to be a global filling of all feeders via the aorta, imitating natural conditions. This was employed by Gillilan (1958), Domisse (1975) and Tveten (1976) for all of the examined specimens, and by Corbin (1961), Hassler (1966) and Jellinger (1966a) only for a part. Aside from the unfeasibility for routine examinations, the large injection volume of several liters necessary even after ligation of the peripheral major arterial trunks poses an additional problem. This was reduced by Gillilan (1958), Domisse (1975) and Tveten (1976) by studying perinatal autopsy cases. This injection technique is well-suited for determining the extraspinal sources of arterial supply and their collaterals. Corbin (1961) and Hassler (1966) additionally carried out selective filling of radicular arteries on the removed spinal cord to demonstrate the inner spinal vessels.

This selective injection technique had already been applied by Adamkiewicz (1881) and Kadyi (1889). Despite numerous collaterals on the medullary surface, complete filling is usually impossible, unless several anterior radicular feeders are injected simultaneously or successively. This deficiency, on the other hand, is advantageous for studying vascular territories on transverse and longitudinal sections if enough fractioned injections can be applied. Nevertheless, only very restricted conclusions concerning intramedullary in vivo hemodynamics can be deduced from postmortem injection experiments (Turnbull et al., 1966; Piscol, 1972).

The difficulties of an adequate filling technique are discussed at length by Noeske (1958), Roll (1958) and Corbin (1961), yet the authors rarely quote exact data on the rate of success.

The quality and completeness of filling depend on many factors:

1. type and quantity of the injected medium;
2. the specimen's state of preservation (autolysis, thrombi);
3. vascular perforation in the vicinity of the injection site or intraparenchymal extravasations;
4. leakage of contrast medium from small disrupted vessels in removed spinal cords;
5. impossibility of filling very small radicular arteries.

For that reason the material for evaluating the outer and inner microvascular architecture must be assembled like a mosaic from a large number of cases in order to obtain a complete picture of all medullary segments. One of the main reasons for divergent results can certainly be seen in these methodological problems which can only be solved at great expense.

The injection techniques applicable for the spinal drainage system differ because global filling is usually impossible from extradural. This experience from postmortem investigations (Breschet, 1828 to 1832; Batson, 1957; Clemens, 1961, Crock et al. 1986) corresponds to results of spinal in vivo phlebography (Theron and Moret, 1978; Vogelsang, 1980). Consequently, the few existing studies on intradural and intramedullary veins are based on macroscopic-microscopic inspection (Quast. 1961; Jellinger, 1966a; Domisse, 1975) or selective intradural filling of radicular veins (Adamkiewicz, 1881, 1882; Kadyi, 1889; Suh and Alexander, 1939; Lazorthes et al., 1962; Gillilan, 1970) Satisfactory postmortem filling through arteries and capillaries into the veins is seldom achieved (Domisse, 1975).

3. Radiographic Techniques

3.1. Postmortem Macro- and Microangiography

Lazorthes et al. (1958) and later Corbin (1961) combined classical methods and injection techniques with postmortem X-ray arteriograms after injecting barium sulphate, thereby contributing essentially to the radioanatomy of the spinal vascular system. Several further studies e.g. by Houdart et al. (1965), Di Chiro and Doppman (1975), Tveten (1976), Doppman et al. (1977, 1979) made use of the excellent contrast characteristics of barium sulphate. With its average grain size of 0,5 μ (Treichel et al., 1977) it is likewise applicable to capillary preparations. Piscol (1972) carried out flow tests with iodine contrast medium, partially using serial angiography.

The possibility of also demonstrating histological structures by the use of extremely fine-grained film and soft X-rays led to the development of microangiography, thus named by Bellmann (1953). This technique of radiological microscopy and microradiography is based on the physical investigations of Cosslet et al. (1957) and Engström et al. (1960). Microangiographical techniques were conducted on the central nervous system with focus on the cerebral vessels (Saunders, 1960; Lazorthes, 1961; Dor and Salomon, 1970; Salomon 1973; Duvernoy, 1978).

Neuroradiological studies of embryonic cerebral development by Voigt and Stoeter (1980) and of experimental cerebral tumors by Schumacher (1981) employed microangiographical techniques. These works include extensive surveys of the literature and methodological discussions on microangiography.

Microangiography of spinal vascular structures has received only sporadic attention. It was demonstrated exemplarily by Saunders (1960) on a fetal spinal cord in the context of an extensive study on the cerebral vessels. The first systematic, strictly microradiographical investigations are the studies by Turnbull, Breig and Hassler (1966) on the cervical spinal cord and by Hassler (1966) on the thoraco-lumbar region; yet these studies only refer to the arterial component. Furthermore, one must mention the microangiographical investigations of the spinal dura mater by Manelfe et al. (1972).

The studies of Tveten (1976) on the spinal vascular system in men and rats are partially based on microradiological methods. Extended application of this method can be found in animal experiments (Doppman, 1975; Doppman and Girton, 1976; Doppman et al., 1977, 1979).

3.2. Spinal Angiography in Animals

Animal experiments using intravital or postmortem spinal angiography have gained importance not only for comparative neuroradiological anatomy (Woollam and Millem, 1955; Tveten, 1976), but especially for the investigation of physiological and pathopyhsiological questions. (Gouaze et al., 1964; Fried et al., 1970; Fried and Aparicio, 1973; Ramsay and Doppman, 1973; Doppman and Girton, 1976, 1977; Doppman et al., 1979)

3.3 Clinical Spinal Angiography

The present state of selective spinal angiography as a relatively safe diagnostical procedure is a result of methodological developments in the early sixties. On the one hand, these consisted of apparative improvements in radiological technology and the possibilities of image subtraction (photographically or through digital image processing). On the other hand, global injection methods were replaced by a selective catheterization of segmental nutrifying arteries or their equivalents. In addition, the application of less neurotoxic contrast media was facilitated by the introduction of non-ionic and almost iso-osmolar substances at the beginning of the eighties.

The now largely standardized technique of selective spinal angiography is based on the pioneering studies of Djindjian and co-workers (1963, 1970, 1975, 1978) as well as Di Chiro and Doppman (1967, 1969, 1971, 1978). Under the present technological conditions, only radicular arteries and sections of the anterior or postero-lateral spinal arteries with calibers of more than 200–400 μ can be demonstrated angiographically. For the determination of blood flow directions in the longitudinal anastomoses, in vivo angiographies of normal spinal cords are most suitable as they reflect the physiological conditions most realistically. According to Adamkiewicz's partial flow theory (1881) deduced from anatomical findings, the blood streams of the radicular arteries divide reaching the medullary surface in two partial streams, one running cranially, one caudally. Consequently, opposing partial flows approach each other in the longitudinal anatomosis between two inflow regions.

Spinal angiography is diagnostically essential in AV malformations (Di Chiro et al., 1967; Doppman et al., 1969; Djindjian et al., 1970; Merland et al., 1980; Vogelsang, 1980; Voigt and Thron, 1986). A second important indication are vertebrospinal tumors (Voigt et al., 1978; Vogelsang, 1980; Djindjan et al., 1981). All surgical procedures on the spinal column that involve a mechanical alteration of the roots should be preceded by a preoperative visualization of the large, anterior radicular feeders (Hilal and Keim, 1972). On the other hand, spinal angiography is of limited value for arteriosclerotic vascular disease or the so-called anterior spinal artery syndrome, although such cases have occasionally been examined (Di Chiro, 1971).

The major limitations of this method are due to the time-consuming examination technique as well as to the insufficient visualization of small vessels and of the venous part of spinal circulation. Even in spinal phlebography (Theron and Moret, 1978), a reflux—impeding mechanism at the dural perforation of radicular veins normally obstructs the flow of contrast medium from the epidural venous plexus into the intradural superficial system.

3.4. Myelography

The structures within the dural sac are indirectly outlined by myelographic techniques that reduce or increase the radiodensity of the subarachnoid space. While the negative contrast through gas myelography only provides an image of gross structures, finer anatomical details can be visualized using positive, especially water-soluble contrast mediums. Consequently, the development of well-tolerated, water-soluble contrast media for examining the complete spinal canal has considerably improved the demonstration of pathologically enlarged vessels on the surface of the spinal cord (Schmidt et al., 1978: Amundsen, 1981). Furthermore, normal vessels of largest caliber (approx. 1000–1500 μ)—usually the posterior veins of the thoraco-lumbar enlargement—become visible as a filling defect.

Myelography based on reliable techniques therefore allows precise identification of pathologically dilated vascular structures of the spinal subarachnoid space (Thron et al., 1983; N'Diaye et al., 1984; Meder et al., 1984). Combined with an improved technique for spinal angiography, i.e., digital subtraction angiography, these procedures led to a considerable increase in detected spinal arteriovenous shunts.

4. Own Investigations

For this radio-anatomical study macro- and microangiographies were performed postmortem on a total of 66 human spinal cords. Following a complete laminectomy, the intact dural sac was excised with the roots severed as peripherally as possible. The only selective factor applied to autopsy cases was an effort to examine space-occupying lesions or vascular spinal diseases. Such pathological cases represented 12% (8/66). Four of the cases are summarized in Table 3 (p. 59). Consequently, the majority of the examined spinal cords was chosen from randomly distributed autopsy cases with varying causes of death. Age distribution had its maximum in the sixth and seventh decade of life and an average of 64 years (36 to 84 years). Male predominated over female by 2:1. Classification according to spinal cord segment and arterial or venous vascular filling shows the following distribution (Table 1):

Table 1

Spinal cord region	Site of contrast injection			
	arterial	venous	arterial + venous	total No.
Cervicothoracic	7	4	1	12
Thoracolumbar	24	13	9	46
Complete spinal cord	7	0	1	8
				66

a) Contrast Medium and Injection Technique

The contrast medium prepared for filling the unfixated specimens consisted of 8 parts of a 90% aqueous suspension of barium sulphate (Mikropaque®) mixed with 2 parts of gelatin solution (25 g gelatin dissolved in 100 ml physiological saline solution at 40 °C) and 4% phenol. In this dilution, barium sulphate suspension reaches at least the precapillary arterioles. Tests with a less concentrated suspension were unsatisfactory due to increased contrast medium extravasations and poorer contrast in the X-ray images. Adding gelatin (heated to 37 to 40 °C) hardens the contrast bolus and prevents contrast medium from leaking when dissecting the fixated specimens. This was occasionally unavoidable, mainly for superficial veins with wide lumen and thin walls.

After dissection of the dural sac, the radicular arteries (or veins) of largest caliber were localized, probed with a blunt lymphographic needle and bound. Further radicular vessels of large caliber in the same filling territory were ligated temporarily along with the cranial end of the cord. Thus, rapid leakage of contrast medium was avoided, while unligated, small caliber vessels permitted injection into the thereby partially open system. Contrast suspension was injected manually under visual control of filling in the superficial vascular network. Depending on the filling achieved, additional vessels were probed and injected in order to procure the most complete vascular visualization possible. On the arterial side, this was most difficult in the mid- and upper thoracic region. For the upper cervical region, ligatures were applied to the proximal basilar artery below the origin of the AICA and to the PICA followed by contrast injection in both vertebral arteries.

b) X-Ray Techniques for Standard Images

Following vascular filling, but before fixation, radiographs were taken using a soft-tissue technique on a mammography device with 25 kV and 0.5 sec, or on a Packard Faxitron with 30 kV and 1.5 min exposure. The images thus obtained allowed evaluation of filling quality and were valuable in determining the plane of section for subsequent microradiography.

c) Preservation

Specimens were fixed in 4% formaldehyde for at least 5 days. Deposition in a stretched position prevented deformations due to incorrect storage, but could not exclude the effects of erratic shrinking processes.

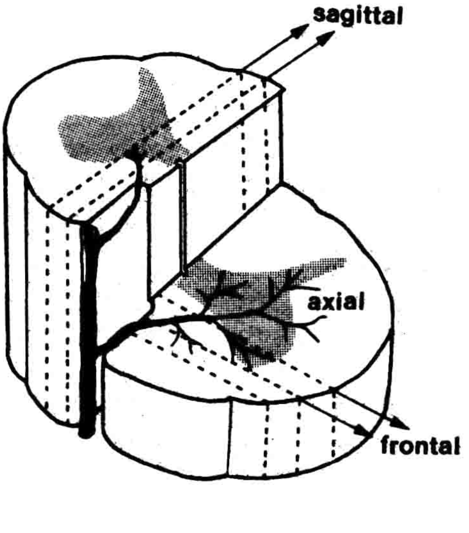


Fig. 1. Orientation of the sections cut for microangiographic evaluation

Table 2. Range of inner vessel diameters for the most important arteries and veins of the spinal cord

Vessel	Spinal cord region: cervical	thoracic (upper two third)	thoracolumbar
Anterior rad. artery	up to 0.6 mm	up to 0.5 mm	0.5–0.8 (-1.0) mm
Anterior spinal artery	0.2–0.5 mm	0.2–0.4 mm	0.5–0.8 mm
"narrow segments"	0.08 mm (C2/3)	0.1 mm	—
rami cruciantes	—	—	up to 0.3 mm
Posterior rad. artery	0.2–0.4 mm	up to 0.2 mm	0.2–0.5 mm
Posterolateral and posterior spinal artery	0.1–0.2 mm	0.1–0.25 mm	0.1–0.4 mm
Sulcal (central) artery	0.1–0.2 mm	0.08–0.2 mm	0.2–0.26 mm
Penetrating branches (vasocorona)	up to 0.05 mm	—	0.06 mm
Ant. and posterior radicular and median spinal veins	0.5–1.5 mm	0.4–1.0 mm	0.5–1.5 (−2.0)mm
Sulcal (central) veins	0.1–0.25 mm	0.08–0.2 mm	0.1–0.26 mm
Radial (peripheral) veins	0.1–0.25 mm	0.1–0.25 mm	0.1–0.2 mm
Transmedullar venous anastomoses	0.2–0.4 mm	0.3–0.7 mm	0.1–0.2 mm

d) Microangiography

For microradiography the specimens were cut with microtome blades into 1–3 mm thick axial (horizontal), frontal or sagittal sections, as seen in Fig. 1. The format of spectroscopic plates used in microradiography allowed a maximal section length of 2.5 cm. A few spinal cords were cut into contiguous sagittal or frontal sections. In most cases, sectioning alternated in order to obtain different views of each spinal cord segment from various specimens.

The slices were prepared for paraplast embedment by alcohol and benzene treatment in an Autotechnikon (model Duo 2.A.). The paraffin-embedded pieces were suitable for microradiography after excess wax had been removed on a hot plate. Contact radiographs were obtained with a special mircostructure X-ray device (Philips X-ray generator PW 1720). Exposure data: 30 kV, 23 mA, 6 to 15 minutes depending on specimen thickness. The film material exposed in direct contact with the specimens consisted of Kodak spectroscopic plates, type 649–0, with especially fine-grained emulsion. Using consistent photographic enlargement, consecutive segments of frontal or sagittal sections could be joined together without gaps, making a longitudinal reconstruction of extensive cord regions possible.

Inner vessel diameters of the most important arteries and veins were determined from the contact radiographs in 10 different specimens with a PET 2001 series minicomputer (Commodore) and a Summagraphics magnetic plate.

Histology was obtained from all cases of suspected spinal cord disease and from the majority of routine autopsy cases (Dr. Christine Rossberg, Department of Neuropathology, Institute of Pathology, University of Marburg, FRG).

IV. Anatomy of the Spinal Cord's Blood Supply

1. Embryology

Only a few investigations and observations exist on the embryonic development of the spinal vessels in man. Ontogenetic studies by His (1887), and more recently by Torr (1957) and Di Chiro et al. (1973) were supplemented by detailed phylogenetic studies, especially those of Sterzi (1904). The examination of early vascularization patterns is facilitated by the apparent similarity of the embryonic development of spinal vessels in higher vertebrates.

The spinal cord vascularization originates from a bilateral capillary network on the ventrolateral surface of the medulla connected with the segmental, dorsal branches of the aorta. After undergoing numerous transformations two primitive longitudinal systems are formed at the same site. The capillary networks expand to the ventral and dorsal sides. Already by the end of the second embryonic month, the primitive ventrolateral longitudinal systems are transformed into a solitary anteromedian longitudinal vessel, the anterior spinal artery. This artery was shown by Torr (1957) and later by Di Chiro et al. (1973) using microangiograms in 10 to 14-week-old embryos to be a quite attenuated vessel. Although at this time differentiation of the vertical systems on the dorsal side already takes place, a plexus-like pattern of vessels remains visible much longer there, as well as on the ventral side of the upper cervical region (Di Chiro et al., 1973). According to His (1887) and Torr (1957), the formation of the anterior spinal artery is the result of a medial movement and fusion of the primitive ventrolateral tracts (analogous to the formation of the aorta), whereas Sterzi (1904) assumes a segmental and irregulary alternating involution of the primitive longitudinal tracts.

The development of the anterior spinal artery is followed by an individually varying regression of the originally 31 bilateral segmental feeders. This numerical reduction is most pronounced in the thoraco-lumbar region, where usually only one artery remains as a ventral feeder. The reduction is completed around the end of the fourth embryonic month. Consequently, the final number and distribution of the arteries supplying the medulla is determined by this time.

The segmental feeders are branches of the dorsolateral somatic intersegmental arteries originating from the aortae. In the thoracic and upper lumbar regions the intersegmental arteries persist as intercostal and lumbar arteries (Hamilton et al. 1959). In the cervical and sacral regions the intersegmental arterial pattern is considerably modified by the development of the vertebral and iliac arteries respectively. Longitudinal anastomoses which are formed between successive intersegmental arteries in the cervical region in postcostal position form a large portion of the vertebral artery. Precostal anastomoses in the cervical and upper thoracic regions persist to form the thyreo-cervical trunk and the superior intercostal stem. Persistence of the post-transverse anastomoses give origin to the deep cervical artery.

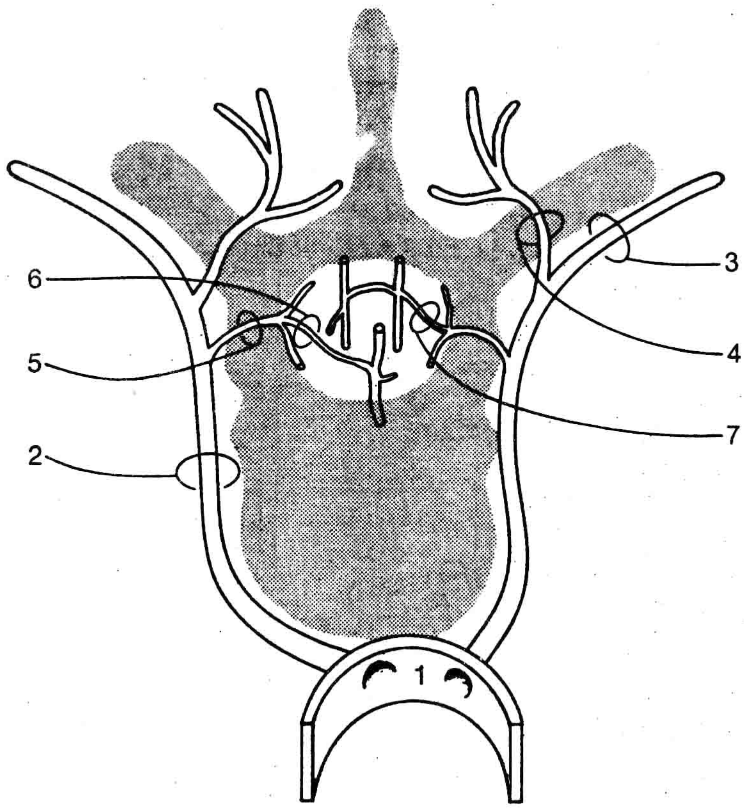
To our knowledge, there are no studies on the embryonic development of the medullary veins.

2. Sources of Arterial Blood Supply and Radicular Feeders

According to embryonic development, feeding vessels to the cervical cord issue from the vertebral artery, the deep and ascending cervical arteries, and the superior intercostal artery. Those to the sacral region come from branches of the internal iliac (lateral sacral and iliolumbar arteries). The segmental arteries of the thoracolumbar region are preserved as the lumbar and intercostal arteries.

From these extramedullary sources, the spinal cord is supplied via the nervomedullary arteries (Fig. 2).

As mentioned above, the embryonic transformation processes result in a reduced segmental supply to the ventral and dorsal aspect of the spinal cord (Fig. 3). But this ontogenetic reduction of feeding vessels is apparently less significant for the nervomedullary arteries (Piscol, 1972). They divide into constant branches that supply the anterior and posterior part of the vertebral



1 aorta, *2* posterior intercostal artery, *3* ventral branch, *4* dorsal branch, *5* spinal branch, *6* anterior radicular artery, *7* posterior radicular artery

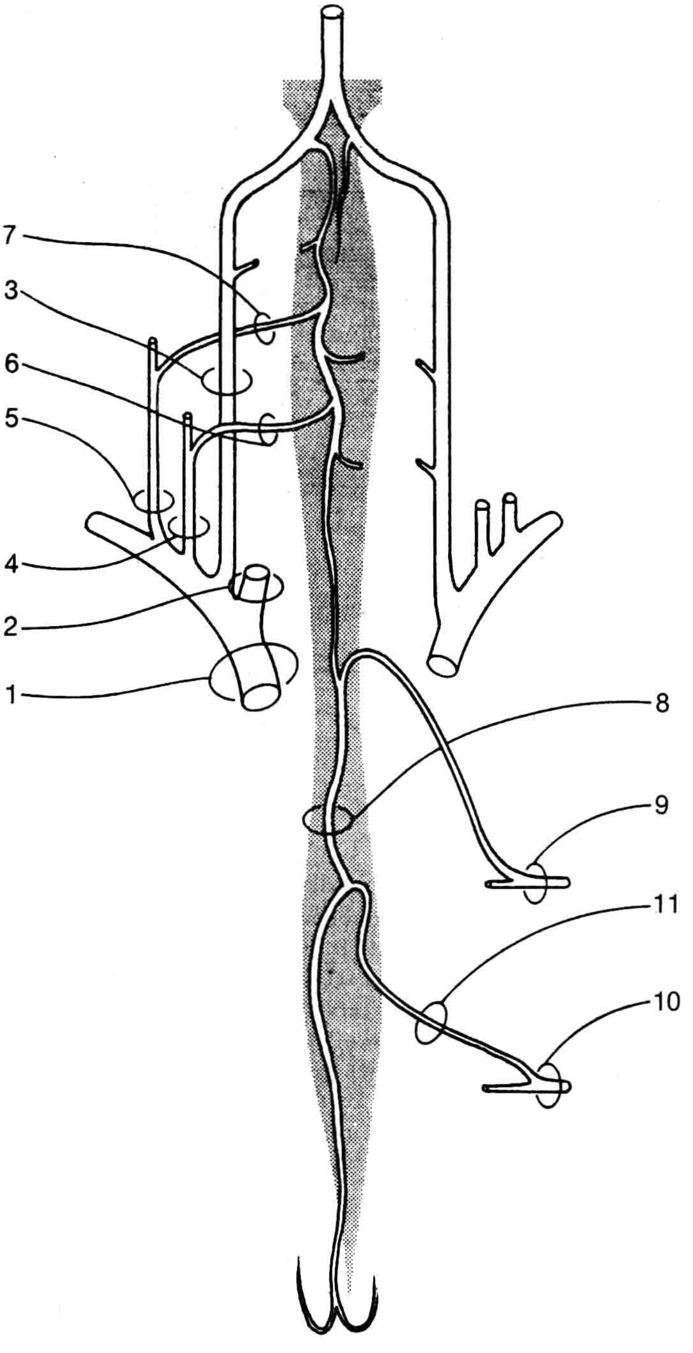
Fig. 2. Arterial supply of the spinal canal and cord (schematic illustration)

canal. According to Manelfe et al. (1972), a radicular branch supplying radix and dura can be demonstrated at almost every segmental level. Only at some levels, nervomedullary arteries further divide into arteries that join the anterior or/and posterior roots to reach the ventral or dorsolateral surface of the medulla. These vessels are called anterior and posterior radicular arteries (Fig. 4). The branching of a nervomedullary artery into an anterior and posterior radicular artery to the spinal cord is, however, the exception in man (Fig. 4) (Jellinger 1966 a). The vessel pierces the dura ventrocaudally of the nerve root.

Number, caliber and entrance level of anterior and posterior radicular vessels were determined by numerous authors. As Jellinger (1966 a) and Piscol (1972) have shown, statistical evaluations of a great number of cases and comparisons with previous studies produced relatively reliable results without essentially diverging from Kadyi's description (1889). Two to fourteen, on the average six anterior radicular arteries persist as branches of the nervomedullary arteries (Fig. 3) (Jellinger, 1966 a; Piscol, 1972). The posterior radicular arteries are reduced less drastically to 11–16 vessels.

The extramedullar sources in the **cervical region** (see Fig. 3) are connected by various collaterals (Lazorthes et al., 1971; Tveten, 1976 a), which can be demonstrated using selective in vivo angiography of the vertebral, deep cervical and ascending cervical arteries. As will be shown later in detail (see chapter V.A.1.), the most cranial feeders originating from the intracranial section of the vertebral arteries may have a relatively small caliber (Lazorthes et al., 1958). The more important feeders with a caliber of 400–600 μ —therefore also called "artère du renflement cervicale" by Lazorthes (1958)—are radicular vessels entering between C 5 and C 7. According to Jellinger (1966 a), the average number of anterior radicular feeders for the cervical medulla is 2–3, with no significant lateralization in this region. The same applies for the cervical posterior radicular arteries, of which approximately 3–4 approach the dorsal cervical medulla with a caliber of 150–400 μ (Jellinger, 1966 a; Piscol, 1972).

The average number of anterior radicular arteries to the **thoracic region** (see Fig. 3) is also 2–3, and for the lumbosacral medulla 0–1 (Jellinger, 1966 a). More often the vessel originates from a left-sided intercostal

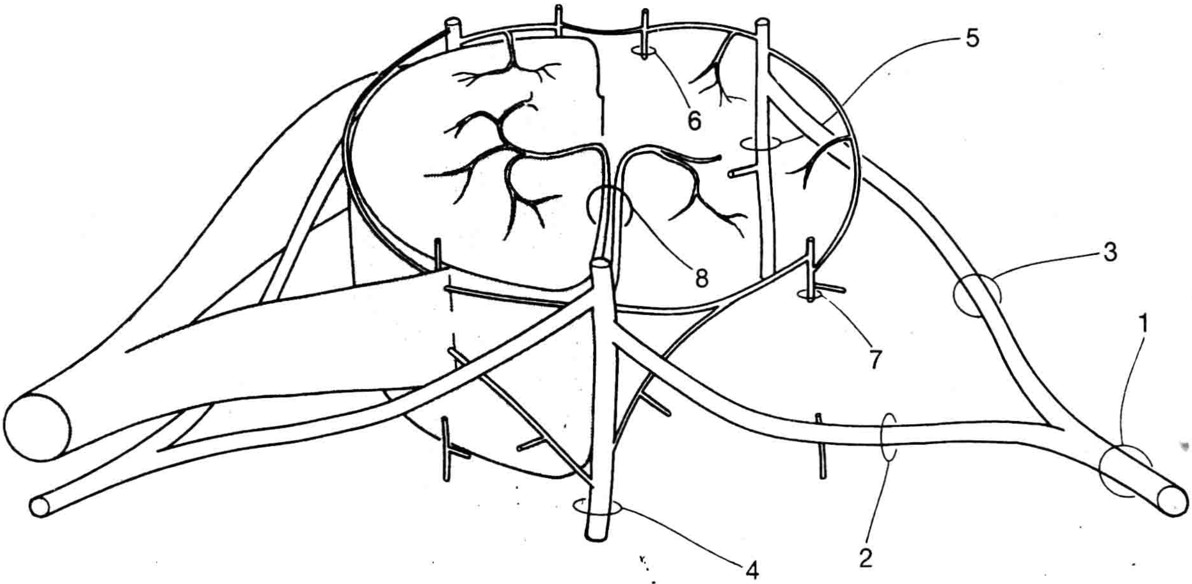


1 brachiocephalic trunk, *2* carotid artery, *3* vertebral artery *4* thyreocervical trunk, *5* costocervical trunk, *6* anterior radicular artery (C6–C8), *7* anterior radicular artery (C4–C5), *8* anterior spinal artery, *9* posterior intercostal artery (T4–T6), *10* posterior intercostal artery (T9–L1), *11* artery of Adamkiewicz

Fig. 3. Main sources of arterial supply to the spinal cord (schematic illustration)

artery, the vessel caliber varies between 550–1200 μ. Smaller ventral feeders with a caliber of about 200 μ are often found in the midthoracic region, less often also at the cervicothoracic transition (Jellinger 1966 a). In the analysis of his cases, Piscol (1972) described an inverse correlation between number and caliber of the ventral radicular vessels supplying the total medulla. These vessels are of large caliber and are concentrated in the cervical and thoracolumbar region when they are few in number ("pauci-segmental type" according to Kadyi [1889]) with a maximum of 5 ventral radicular feeders). A large number of feeders ("pluri-segmental type" with 6 or more arteries) results in small calibers.

In the **thoracolumbar region**, one of the anterior



1 nervomedullar artery, *2* anterior radicular artery, *3* posterior radicular artery, *4* anterior spinal artery, *5* posterolateral spinal artery, *6* posterior spinal artery, *7* transverse and longitudinal interconnections between the main longitudinal trunks (pial network) giving origin to the perforating branches of the vasocorona, *8* sulcal (central) arteries

Fig. 4. Arteries of the spinal cord (schematic illustration)

radicular arteries is always distinctly dominant in caliber and was therefore termed the great radicular artery by Adamkiewicz (Fig. 3). In 73% of all cases it enters from the left side with its origin usually between T 9 and 12 (62%), seldom lower in the lumbar region (26%) or higher between T 6 and 8 (12%) (Jellinger, 1966 a).

The number of dorsal radicular arteries is reported with an average of 8 (Piscol, 1972) to an average of 9–12 (Jellinger, 1966 a) for the total thoracolumbar region. No lateral preference is observed: the vessel calibers lie between 150–400 μ. The existence of a great posterior radicular artery, corresponding to the anterior one and possessing a distinctly greater caliber than the other posterior radicular arteries, is affirmed by a few authors (Gillilan, 1958; Lazorthes et al., 1958; Jellinger, 1966 a), but rejected by others (Corbin, 1961; Piscol, 1972). Consequently, the total 11–16 posterior radicular arteries display greater homogeneity in distribution.

3. Extramedullary Venous Drainage

Venous blood from the medulla drains into a system of longitudinal venous anastomoses lying on the surface of the spinal cord (Fig. 5) (anterior and posterior median spinal veins), and from here into anterior and posterior radicular veins. Communication with veins of the posterior cerebral fossa is found at the craniocervical junction. The anterior median spinal vein often continues caudally as a large terminal vein which runs ventrally of the filum terminale to the end of the dural sac.

The total number of medullary radicular veins amounts to 30–70 (Kadyi, 1889; Tureen, 1938; v. Quast, 1961; Jellinger, 1966 a), with an average of over 50. An unequivocal numerical dominance of anterior or posterior radicular veins is not found. Jellinger (1966 a) calculated an average of 23 ventral to 25 dorsal outflows, v. Quast (1961) 30 to 26. This almost symmetrical anterior-posterior distribution is accompanied by a minimal fluctuation in the segmental distribution. A significant reduction should only occur in the uppermost cervical and sacral segments. Likewise, no obvious lateral preference can be observed. *Consequently, a much more pronounced symmetry and metameric structure is preserved in the radicular drainage system.* Whereas the anterior radicular veins have a caliber between 100 and 1000 μ, some of the posterior radicular