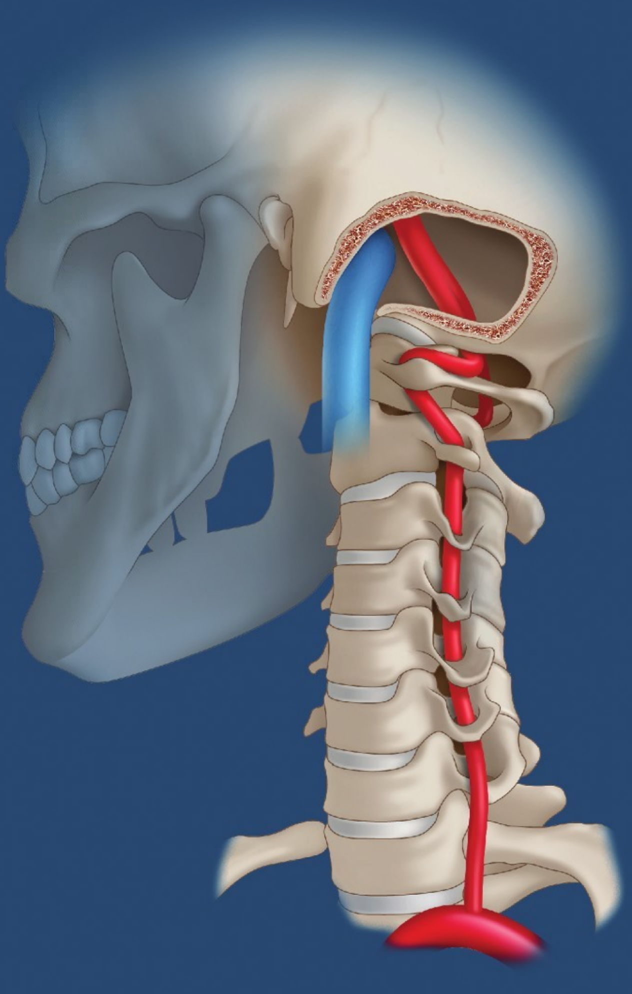
BERNARD GEORGE | MICHAËL BRUNEAU | ROBERT F. SPETZLER

PATHOLOGY AND SURGERY AROUND THE VERTEBRAL ARTERY



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Pathology and surgery around the vertebral artery

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Foreword

With great anticipation and pleasure I have studied the 45 notable chapters elaborated in this voluminous monography comprising contributions of colleagues from 22 neuro-science centers throughout the world. Drs. B. George, M. Bruneau, and R.F. Spetzler deserve my admiration for the successful coordination of this homogenous publication. Around 280 pages have been processed by Drs. M. Bruneau and B. George, who have initiated and orchestrated this immense collective and creative endeavor.

The first seven chapters provide us with comprehensive descriptions, enhanced by excellent illustrations of the essential elements related to embryology, anatomy, and physiology of the cervical spine and cervico-cranial junction; the anatomy and radiology of the vertebral artery, their branches, their courses, and variations; followed by four chapters portraying the non-invasive visualization technology of CTA, MRA, ultrasound technology, and vessel flow monitoring.

While studying these chapters, my mind immediately reminisced on the 1950s when radiologists and neurosurgeons achieved direct percutaneous puncture of the vertebral artery in its various cervical segments and were able to successfully perform serial and even stereoscopic angiograms on their patients. The results were published by Sugar (1949), Lindgren (1950), Sutton (1953), Sjögren (1953), Sheldon (1956), Loïfgren (1958), Huang and Wolf (1964–1975), Newton and Potts (1974), and Salamon and Huang (1976).

My personal career in neurosurgery was related to my success in routine percutaneous vertebral angiography beginning in January 1953. The observations gained during the following 4 years on 250 patients with various vertebro-basilar vascular diseases and anomalies; also, the anatomical studies on cavader heads were published in 1957 by Thieme (See reference 57, p. 537, Chapter 34 in this monography). I am delighted to recognize and praise the progress in neuroscience that has been accomplished within the last 60 years. These advances are clearly and precisely presented in this monography.

The introduction of catheter techniques for angiography had already gained a foothold in the 1950s (Radner 1951, Seldinger, 1953) and subsequently replaced other methods during the following two decades. The astonishing and notable accomplishment in several fields of the medical industry since the 1970s has shaped the development and facilitated immensely the method and mode of performance of cranio-spinal angiographies. Catheter technology as well as the acquisition of non-invasive visualization technology is all concisely explained in this monography.

Thirty-four chapters of the monography are devoted to the diverse treatment options of a wide spectrum of diseases in different segments of the cervical spine and vertebral artery, cervico-cranial junction, foramen magnum, and jugulare. Worldwide leading experts and their coworkers discuss their innovative concepts for precisely targeted approaches and skillful removal of the lesions, repair and revascularization of the vertebral artery in various segments and endovascular treatment of saccular aneurysms and arteriovenous fistula. The texts are straightforward, informative, and concise, and are accompanied by many outstanding and instructive color drawings and radiologic and surgical pictures. Some of these innovative surgical procedures will surely result in the forging of new avenues in neurosurgery.

The final chapter is devoted to surgical complications, which are very relevant aspects to consider in our never-ending learning process in order to effectively treat our patients.

I am convinced this unique monography will find great interest, and be a source of stimulation and education for neurosurgeons, neuro-radiologists, neuro-otologists, neuro-orthopedists, neurologists, and clinical neurophysiologists.

M. Gazi Yaşargil, MD
Little Rock, USA

Foreword

When I have been aware of Dr. Michael Bruneau's project to write a book on pathology and surgery around the vertebral artery in close collaboration with two well-known masters in neurosurgery, Drs. Bernard George and Robert F. Spetzler, I have immediately supported his project with great enthusiasm.

Writing a book on such a difficult topic covering from degenerative disorders to the craniocervical junction tumors needs the participation of many experts listed in the table of contents and almost the support and active contribution of Drs. Bernard George, Michael Bruneau, and Robert F. Spetzler, whose competence is unanimously recognized.

This monograph is very impressive and informative, bringing for the first time an original and complete overview on all complex pathologies where VA is concerned.

It is likely that this book will become the classic on this topic and the reference for contemporary neurosurgeons. Reading it is an effort that is amply repaid by the satisfaction it provides.

Jacques Brotchi, MD, PhD
Brussels, Belgium

Foreword

This book is an achievement of more than 30 years of work around the vertebral artery. It started in 1977 with a saphenous vein graft bypass between the subclavian artery and the distal vertebral artery to exclude an aneurysm at the C3 level. At the beginning, with my friend Claude Laurian, a vascular surgeon, we mostly developed techniques of revascularization after ischemic problems. In fact, while we thought indications of vertebral artery surgery would be rare and restricted to intrinsic lesions, very soon we were faced with other pathologies, mainly tumors located in close vicinity of the vertebral artery. It became obvious that a tumor encasing or even only compressing or displacing the vertebral artery could be more easily and completely removed if the vertebral artery was controlled proximally and distally prior to its resection. As early as 1980, it appeared that control of the vertebral artery could also help to reach some blind corners such as the anterolateral part of the foramen magnum and cranio-cervical junction, the posterolateral part of the cervical vertebral bodies and ultimately the jugular foramen. At the foramen magnum level it led to the description of the posterolateral and anterolateral approaches, later renamed far and extreme lateral. At the cervical level, the oblique corpectomy is now used to enlarge the spinal canal and the intervertebral foramen in spondylotic myelopathy and radiculopathy or to approach tumors located anterior to the spinal cord. At the jugular foramen level, it provides a posteroinferior access which avoids or decrease the need of petrous bone drilling.

Altogether we have now performed more than 1700 surgeries around the vertebral artery. Surprisingly it is at the upper cervical level where the vertebral artery has the most complex course and is the most difficult to expose; its exposure has become very popular. Many publications on surgery at the cranio-cervical junction level witness it. Conversely lower in the neck, where the vertebral artery has a straight and linear course, surgeons are still more reluctant to work on it. This book is an attempt to demonstrate, hopefully as clearly as possible, the feasibility of approaching, controlling and repairing the vertebral artery at any level of its cervical and intracranial course. It also tries to display all the pathologies that may involve this vessel.

Michaël Bruneau must be thanked for the incredible efforts he made to write with me several chapters of this book and to collect chapters from most of the experienced surgeons in this field. He was trained in my department and has become a real expert in vertebral artery surgery as demonstrated in several illustrative cases in this book. Among the contributors, I have a particular thought for Pierre Lasjaunias who gave us the possibility to reorganize from a previous publication the chapter on embryology that he will never see. Robert Spetzler not only provided with his team several chapters but also was kind enough to accept to be one of the editors of this book as an undisputable guarantee of quality. My warm-hearted thanks also go to all the contributors of this book. Most of them are friends who have supported me all along my career. I take their contributions as a precious gift. I also feel privileged that two eminent neurosurgeons Pr G.Yasargil and Pr J Brotchi have accepted to write a preface. The editorial team of Springer Verlag has also to be thanked to have accepted and organized so well the publication of this book.

I hope the efforts of all of them will reach the goal of this book which is to make vertebral artery surgery accessible to most surgeons.

Bernard George

History of vertebral artery surgery

P. Fransen, B.J.M. Pirotte

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History of anatomical and angiographic description of the vertebral artery

The anatomical features of the vertebral artery have been described since the Renaissance. The anatomical description reported two centuries later by Jean Baptiste Bonhomme, practicing as surgeon and anatomist in Avignon, France, during the eighteenth century, shows a very detailed understanding of the trajectory and branches of the vertebral arteries, including the fact that this artery was a major blood supplier of the brain (Figs. 1 and 2). However, the real knowledge of its anatomy could only be assessed after the invention of cerebral angiography, and therefore, anatomy and angiography cannot be separated.

The first knowledge of the vertebral artery came from the studies of anatomists such as Willis (1664) and Quain (1844) (1).

In the early 1920s, Moniz, professor of neurology in Lisbon, started his work on imaging of the brain that could until then only be observed indirectly through Dandy's method of air ventriculography.

Moniz first tried to obtain images of the brain by administrating bromine to his patients, first orally, and then by direct injection in the carotid artery. Failing to obtain more than a faint and inconstant visualization of the brain, and after the death of one patient, he and his team decided to use iodine rather than bromide. He felt that iodine, having an atomic weight of 127, had a better chance to be seen on film than bromide with its atomic weight of 80 (2).

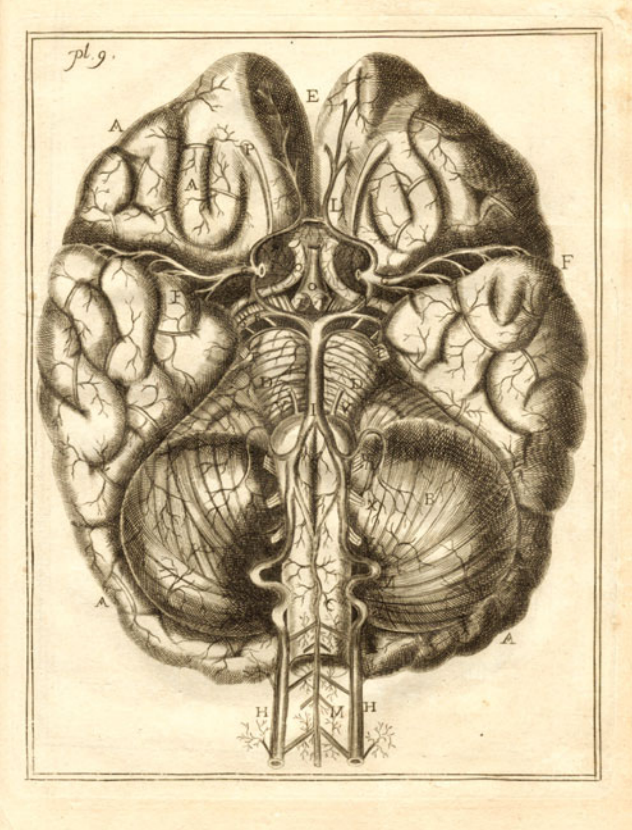

Fig. 1. – Illustration of the anatomy of both vertebral arteries, and its relationships with the spinal cord and the medulla. In *Traité de la céphalotomie ou description anatomique des parties que la tête renferme* by Jean Baptiste Bonhomme, sworn surgeon, published in *Avignon François Girard*, imprimeur Libraire, St. Didier, France, 1748. Private collection, copied with permission.

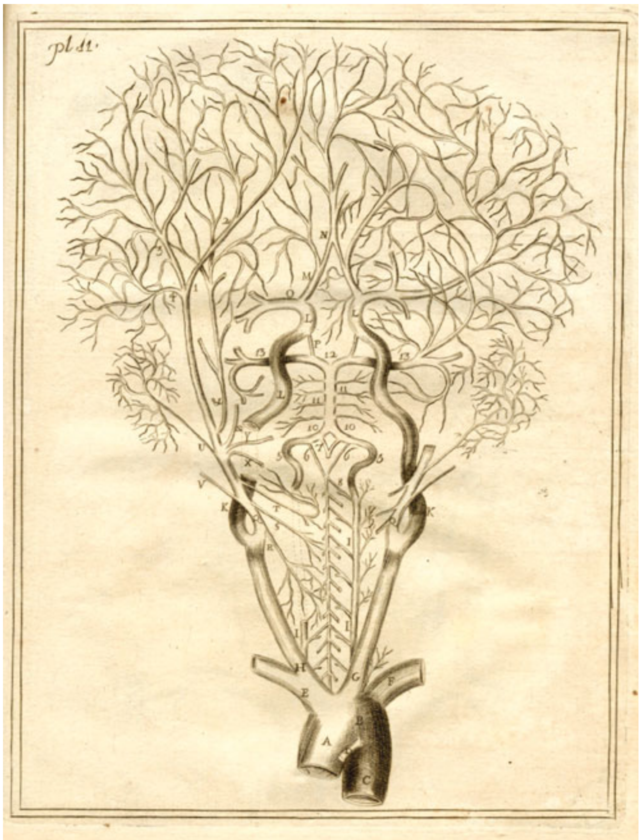

Fig. 2. – Detail of the vascular anatomy of the brain, including the posterior circulation. In *Traité de la céphalotomie ou description anatomique des parties que la tête renferme* by Jean Baptiste Bonhomme, sworn surgeon, published in *Avignon François Girard*, imprimeur Libraire, St. Didier, France, 1748. Private collection, copied with permission.

The first visualization of portions of the carotid artery in the Sylvian fissure was obtained in June 1927. In the following 4 years, Moniz wrote 62 papers and his first book on cerebral angiography was published in Paris in 1931 (3).

Refining his technique even further, it was Moniz again who performed the first vertebral angiography in 1933 (4). The prolific Moniz received the Nobel Prize in 1949, not for his work on angiography, but for introducing frontal lobotomy, a procedure that became popular before being subsequently discarded (5).

More recently, Matula et al. (6) did an anatomical, angiographic and colour Doppler study, further investigating the morphologic variations and frequencies of the first vertebral artery segment and its clinical implications. Bruneau et al. (7) reported in 2006 an evaluation of the incidence of anatomical variations of the V2 segment of the vertebral artery as these may lead to inadvertent injury and potentially serious complications during lateral or anterior surgical approaches. Finally, Civelek et al. (8) reviewed in 2007 the anatomical structures and landmarks of the anterolateral approaches to the cervical spine, further refining our knowledge about surgery for and in the vicinity of the vertebral artery.

History of surgery

In the nineteenth century

Surgery specifically dedicated to disorders attributed to the vertebral artery really began during the nineteenth century. In those days, vertebral artery surgery was merely limited to the ligation of the artery at different levels on its course. As angiography was not possible, there was not only no preoperative imaging, but also no control of the accuracy of the ligature placement.

Matas, of New Orleans, reviewed in 1893 the experience of vertebral artery surgery up to that time (9). He reports that despite the absence of proper imaging techniques, it was Dietrich who in 1831 first proposed the ligation of the distal vertebral artery in the occipito-atloid region and in the atlantoaxial region. The objectives of these procedures have unfortunately not been clearly detailed at that time. A few years later, Velpeau (1833) suggested the ligation of the vertebral artery in its proximal portion.

Maisonneuve (1853) successfully ligated the vertebral artery at the level of the sixth cervical vertebra for bleeding control after a stab wound. The patient died 1 month later due to septic cerebral embolism from the infected wound. Smithes performed the first elective ligation of the vertebral artery in 1864, in an attempt to control bleeding after a tuberculous abscess had eroded the lateral wall of the proximal vertebral artery. There too the patient died 3 weeks after surgery from cerebral complications. Alexander (10), from Liverpool, performed several elective ligations of both vertebral arteries in one session in order to treat uncontrolled seizures or other neurological conditions.

Matas reported in 1888 the very first successful excision of an aneurysm of the vertebral artery between the occiput and the atlas from a posterior approach.

In the twentieth century

Although wars frequently contribute to giant leaps forward in terms of surgery, during and after World War I, neck wounds remained frequently fatal, and reports of vertebral artery surgery were not common. It was only after World War II that the use of Moniz's cerebral angiography became more widespread, allowing better knowledge of conditions such as vertebral arteriovenous fistulas and false aneurysms. In 1946, Elkin and Harris reported 10 cases of arteriovenous aneurysms caused by shrapnel-induced lesion during wartime, and recommended treatment by proximal and distal VA ligation or by direct approach to the fistula (11). Their findings were confirmed by Wilder Penfield of Montreal.

Also, angiography allowed detection of vertebral artery and basilar artery aneurysms, and rationalizing of their surgical treatment. Dandy described with precision the sites of elective ligation of the vertebral artery, proximal to the sixth vertebra, between the atlas and the axis and between the occiput and the axis (12). He was also one of the first to describe fatal thrombus propagation from the vertebral artery to the basilar artery following vertebral artery ligation.

In the late 1950s, surgeons attempted to relieve brain ischemia by vertebral artery reconstruction. Crawford et al. reported in 1958 their results on the surgical treatment of basilar insufficiency (13). Others reported lifting extrinsic compression of the proximal vertebral artery by osteophytes or constricting bands, but most of the reported surgery was about treatment of subclavian steal syndrome.

Towards the microsurgical era

Yasargil was the first to report the use of the operative microscope in 1969 for ligation of a saccular aneurysm at the junction of the vertebral arteries (14). This major technical breakthrough allowed the 1970s to witness – amongst others – the development of anastomosis and bypass surgery involving the vertebral artery. In 1970, Wylie and Ehrenfeld (15) described the anastomosis of the proximal vertebral artery to the common carotid artery, whilst in 1975 subclavian vertebral anastomosis was reported by Carney et al. They also presented in 1977 the first vein bypass from the common carotid artery to the vertebral artery (16–18).

George and Laurian reported their experience in 1980 with surgical approaches on the entire length of the vertebral artery, with special reference to the third portion, describing a pathway between the sternocleidomastoid muscle and the internal jugular vein, allowing to treat cases involving spinal arteriovenous fistulas, aneurysms and dysplasia of the vertebral artery, as well as neurinomas or meningiomas involving the spinal canal (4, 19). Finally, Rhoton's team reported relevant microsurgical anatomical studies of the vertebral artery in the vicinity of the occipital condyles (20) and in the lower cervical spine (21).

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Embryology of the vertebral artery[1]

2

B. George, M. Bruneau

Table of contents

General development of brain and vessels

The development of the cerebral arteries is a continuous and adaptative process of vascularization to changes in the shape, size and metabolism of the brain. It is a mechanism of reciprocal interactions in which the blood supply is constantly adapted to the metabolic requirements of cerebral activity. Secondary morphologic changes of the neural tissue reshape the arterial tree. At the earliest stages of development as the neural tube is still open, the nutrients diffuse directly from the amniotic fluid through the ependymal surface of the tube (1). As soon as it closes after separating from its ectodermal coverings, the neural tube is surrounded by connective tissue derived from the neural crest that forms the meninx primitiva. This provides the initial nutritional support for the closed neural tube (1, 2) by a mechanism of diffusion through its external (meningeal) surface. This stage can be named *prechoroidal stage*. Then as the cerebral tissue continuously increases in volume, this mode of nutrition from the meninx primitiva comes to be supplemented by local invagination of the meninx into the ventricular lumen to constitute the choroid plexus so that the supply to the neural tube then comes from its both external and ependymal surfaces (1, 3–5). This stage can be called the *choroidal stage*. Then with the continuous increase in thickness of the cerebral mantle, the metabolic demand induces an intrinsic angiogenesis from the superficial vascular system (1). This stage corresponds to the *parenchymatous stage* of cerebral vascularization. This new intraneural vascular bed is connected with the afferent arterial pattern already determined at a previous stage, the basic morphology of which therefore persists (6). Due to considerable increase in volume of the brain and the modifications that simultaneously occur in the proximal part of the afferent vessels, additional changes appear. Starting from the basic morphologic scheme and via the continuous anastomotic surface network, shifts and incorporation of distal territories may take place, governed by haemodynamic rules related to metabolic activity of the brain tissue. These secondary variations on a theme constitute the ground for the variants that will be observed in the future final arrangement.

The embryonic period

The neural tube is the first and, in size, the most prominent organ to develop during embryogenesis (7). Following the early stages of division of the first embryonic cells, the neuroectoderm differentiates to constitute the neural plate at the end of the third week. After folding longitudinally, it becomes the neural tube. The closure occurs near the junction of the hind-

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[1] Rewritten from P. Lasjaunias and A. Berenstein, in collaboration with C. Raybaud, *Surgical neuro-angiography*, Springer-Verlag Berlin Heidelberg, 1990.

brain and spinal cord at the level of the fifth somite, and then proceeds in zipper-like fashion cranially and caudally (8). The anterior neuropore closes at the 25th day at the cephalic end of the tube where it forms the lamina terminalis, which corresponds to the anterior telencephalic extremity of the third ventricle (or telencephalon impar). The caudal segment of the neural tube constitutes the neural portion of the spinal cord. In the following days the cephalic end of the neural tube undergoes flexures and segmental dilatations, the latter forming the three primitive vesicles: from rostral to caudal, the prosencephalon or forebrain, the mesencephalon or midbrain, and the rhombencephalon or hindbrain (rhombencephalon derives its name from the diamond shape of the fourth ventricle). At this stage (beginning of the fifth week) the cephalic neural tube is a closed segmented tubular structure made up of three vesicles buried within a dense connective tissue, the meninx primitiva. Endothelial cells individualize and assemble within this membrane to constitute angioblastic cords (9, 10) that canalize secondarily to form a plexiform vascular network around the neural tube. It is still impossible at this stage to find any differentiation between arteries, veins or capillaries. When the cardiac primordium has formed, with the cardinal veins and the two primitive aortas, the perineural vascular network establishes communications with this vascular system (during the fifth week). Then the perineural vascular network changes; its most superficial layer becomes organized into arterial and venous channels, whereas the deepest one, closest to the neural tissue, constitutes a capillary network. These changes are due to major signalling molecules involved in vascular development and differentiation: the angiopoitins, the endothelins, various growth factors and the Notch receptors (11). At the cephalic level, those superficial channels with a venous function form the primary head sinuses located on each side of the neural tube (12–14). The paired arterial structures of the carotid system end ventral to the prosencephalic vesicle (6). Ventral to the rhombencephalon, two arterial channels can be recognized, one on each side of the midline (6): the ventral *longitudinal neural arteries*. Their caudal extremities communicate laterally with the carotid system through the *first segmental artery*, the *proatlantal artery*. At the level of the trigeminal nerve, another transient communication is established, the *trigeminal artery*. Additional transient anastomoses supply the ventral neural longitudinal arteries, in particular the *hypoglossal artery* at the level of the XII cranial nerve (Fig. 1).

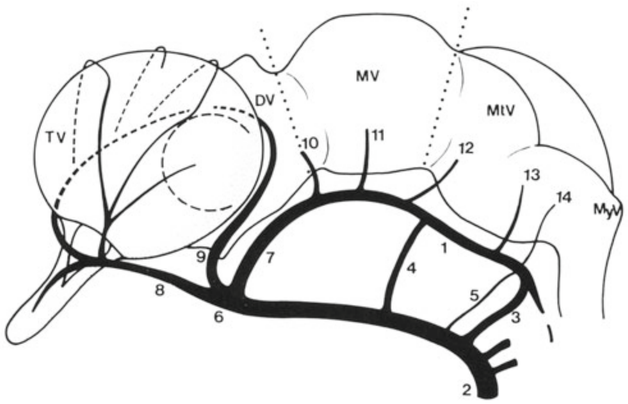

Fig. 1 – Development of the arterial vascularization of the brain. The longitudinal neural artery (*1*) of the ventral aspect of the rhombencephalon is supplied by branches of the primitive common carotid artery (*2*), the proatlantal artery (*3*) caudaly, the trigeminal artery (*4*) cranially, and by the hypoglossal artery (*5*). The longitudinal system of anastomoses between the cervical intersegmental arteries has not yet evolved into the vertebral arteries. More cranially, the primitive carotid artery ends as a rostral (*6*) (olfactory artery) and a caudal (*7*) (posterior communicating artery) division. The anterior branch subdivides into the anterior cerebral (*8*) and future anterior choriodal (*9*) arteries and both encircle the neck of the telencephalic vesicle (*TV*) and anastomose with each other. Their lateral branches form the pericerebral arterial network of the hemispheres, including what is to become the middle cerebral artery. The posterior branch of the primitive carotid artery sends secondary branches toward the diencephalon (*DV*) (posterior choroidal arteries, *10*), the mesencephalon (*MV*) (collicular arteries, *11*), the metencephalon (*MtV*) (Superior cerebellar artery, *12*). It connects with the longitudinal neural artery, thereby causing the trigeminal artery to regress, while the development of the vertebral artery supplies the caudal artery system place of the proatlantal artery, which then also regresses. 13, Anteroinferior cerebellar artery; posteroinferior cerebellar artery(14), (MyV), myelencephalic vesicle.

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Then the encephalic neural tube subdivides at the end of the fifth week from three vesicles into five vesicles.

Obviously, these morphologic changes associated with the ongoing growth of the neural tube require an adaptation of the vascular system to fulfil the metabolic needs of the parenchyma (2). The most significant change in the arterial tree at this stage is the development at the ventral aspect of the prosencephalon of two branches from the carotid tree (6, 15):

– The anterior or rostral branch subdivides and makes up an arterial ring around the neck of each telencephalic vesicle. In view of the prominence of the olfactory lobe at this stage, this artery is called either the olfactory or the telencephalic artery.

– The posterior or caudal branch reaches the cephalic end of the ipsilateral ventral longitudinal neural artery to constitute the *posterior communicating artery*. This leads to regression of the preexisting transient anastomoses mentioned above (trigeminal and hypoglossal arteries) (6): the involution happens between the 8- and the 12-mm stages.

Simultaneously, in the 4-mm embryo, ventral longitudinal neural arteries tend to fuse at the midline to form the *basilar artery*, and therefore the posterior segment of the circle of Willis. This fusion is usually completed by the 8-mm stage. Failure of this fusion results in duplication of the BA (16).

By the end of the sixth week, the vascular system of the brain is intrameningeal. It consists of a deep perineural capillary network, still strictly meningeal, outside the neural tube, supplied and drained by a more superficial arterial and venous network. The metabolic supply to the brain tissue is provided by simple diffusion from the vascularized meninx primitive around the tube (1, 2, 13). It is of interest to note that what will become the cerebral arterial tree is already recognizable, although very primitive: the internal carotid and its telencephalic branches, the basilar artery and the posterior communicating channels with their mesencephalic branches (6).

During the sixth to eighth weeks the meninx primitiva, still a dense connective tissue, penetrates the ventricular lumen and invaginates the ependymal layer to constitute the choroid plexuses. These develop first at the diencephalic–telencephalic junction (velum transversum), at the posterior lip of the foramen of Monro. Another choroid plexus develops in the roof of the diencephalic vesicle (the choroids plexus of the third ventricle). At the level of the fourth ventricle, the invagination of the choroid plexus occurs along a transverse line that delineates the fourth ventricle with the metencephalic portion rostrally and the myelencephalic portion caudally. The latter will later partially disappear in humans to leave in its place the opening of the foramen of Magendie. From the posterior branch of the ICA, another artery courses towards the choroid plexus of the third ventricle and will become the posterior choroidal or diencephalic artery. At the level of the fourth ventricle, the arterial supply to the choroid plexus arises from the basilar artery via the future inferior anterior cerebellar artery. The longitudinal anastomoses that are established at the same time at the cervical level between the segmental arteries from the subclavian artery to the craniocervical junction constitute the VA (6); meanwhile, the proximal segmental arteries regress progressively (see below).

Arising from the anterior branch of the telencephalic artery, vessels will grow on the medial and lateral surfaces of the telencephalic vesicles representing the future hemispheric territories of the anterior cerebral and middle cerebral artery (6). Similarly the mesencephalic artery develops together with the collicular region and the anterior superior cerebellar artery follows the growth of the cerebellum (6). In contrast, the posterior inferior cerebellar artery is still a minor branch of the vertebral artery which only supplies the dorsal aspect of the medulla (6).

Then the embryonic period ends. It has been characterized by the shaping of the rostral extremity of the neural tube and by the simultaneous shaping of its arterial tree.

The foetal period

When compared to the embryonic stage, the foetal period is characterized by intense cellular multiplication. Histogenesis is accompanied by penetration of the cerebral parenchyma by vessels originating from the perineural network. These additional vessels develop from the already existing network, which increases in size but does not change in gross morphology. Finally while the intraparenchymal circulation develops, the vascular organization of the meninx primitiva regresses and disappears. The connective tissue of the meninx primitiva undergoes changes through vascularization and cellular condensation. The vascularization leaves behind a fluid space: the subarachnoid space; its boundaries are constituted by cellular condensation forming the connective tissue coverings, that is, the pia mater, the arachnoid, the dura mater and the bony vault.

In humans the degree of vascular maturation in the second half of pregnancy has been histologically studied by Kuban and Gilles (17). The vascular channels are primitive vessels that cannot be distinguished as arteries or veins. It is even possible that they may retain until birth the capacity to differentiate into either arteries or veins according to need, or to disappear. The leptomeningeal vessels at the base of the brain present a muscular layer more conspicuous than those of the convexity.

Vascular development

As mentioned above, at an initial stage of development there are *two aortic trunks* (the ventral and dorsal aorta) which will evolve to form essentially the carotid system and two arterial channels ventral to the rhombencephalon, one on each side of the midline (6), the *ventral longitudinal arteries* (Fig. 2). This longitudinal neural system will give origin to the VA, the basilar trunk and the spinal artery. Between the carotid group and the longitudinal system exists a certain number of arterial bridges which correspond to metameric or segmental vessels and which become *carotico-vertebral anastomoses* (Fig. 3). These anastomoses accompany for each metamere the corresponding peripheral nervous rudiment and establish a dorsoventral connection. These are temporary but they do not disappear simultaneously and may not do so at all: they are the *trigeminal*, the *otic*, the *hypoglossal* and the two types of *proatlantal* arteries. The first four arteries anastomose the ICA with the vertebro-basilar system while the last one connects the ECA with the VA. Similar dorsoventral connections can also be found lower in the neck: the first, second, third, fourth, etc., segmental arteries. At the end of the second phase (6) the ventral and dorsal portions of the segmental arteries disappear and the first segmental artery takes over the supply of the longitudinal neural artery. A certain number of longitudinal anastomotic channels have formed between these segmental arteries which becomes the VA; in fact, the VA represents the persistence of six to seven consecutive intersegmental arteries, each of which can be the site of arterial agenesis leading to specific variations. Such variations must bypass the unformed segment to provide the necessary blood supply to the posterior fossa. At the upper cervical level these deviations are usually described as an 'aberrant course' of the distal VA which in fact corresponds to the recruitment of the lateral spinal channel (see below).

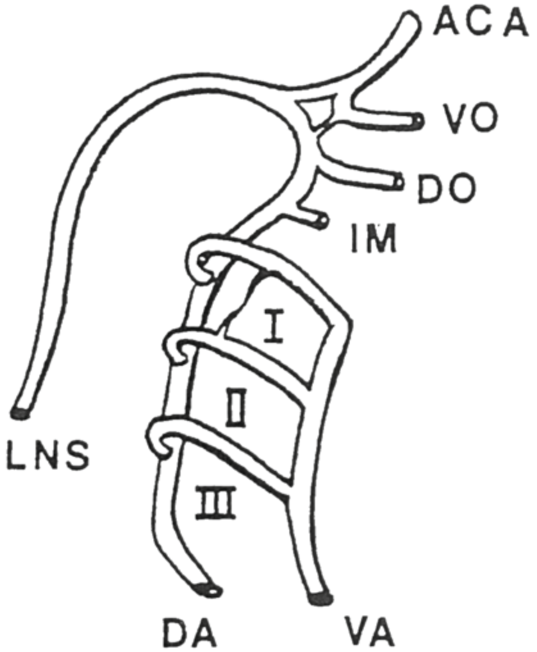

Fig. 2 – Illustration of he embryonic development of the aortic arches in the cranio-cephalic region.
I, II, III aortic arches numbered in the craniocaudal direction. *ACA:* anterior cerebral artery, *VO:* ventral ophtalmic artery, *DO:* dorsal ophthalmic artery, *IM:* primitive maxillary artery, *LNS:* longitudinal neural system, *DA:* dorsal aorta, *VA:* ventral aorta.
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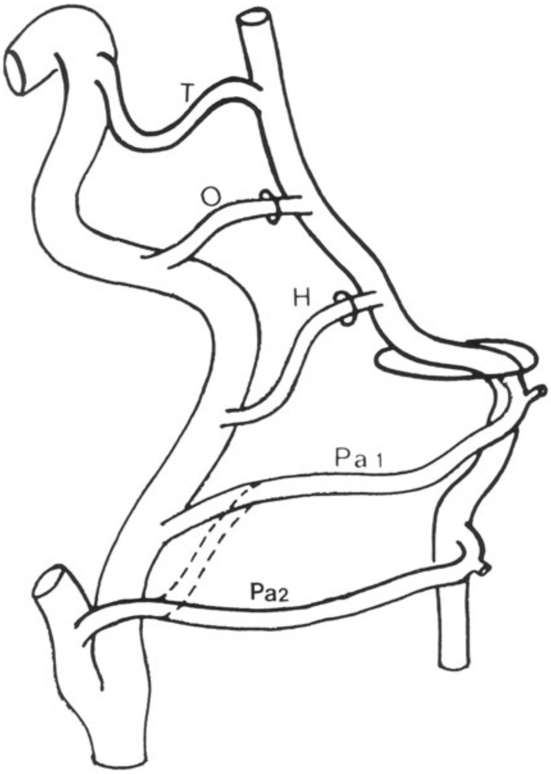

Fig. 3 – Diagrammatic representation of the caroticovertebral anastomotic channels. *T*: trigeminal artery; *O*: otic artery; *H*: hypoglossal artery; *PA 1*: proatlantal artery type 1; *PA 2*: proatlantal artery type 2. Reprinted by permission from Lasjaunias, P et al.: The occipital artery. Neuroradiology 15: 31-37, 1978.
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Some of the segmental vessels may persist in the adults. In fact, the first segmental artery corresponds to the type 1 proatlantal artery anastomosing between the ICA at C2 to the VA; the type 2 proatlantal artery corresponds to the second segmental artery connecting the ECA to the VA (Fig. 4). The hypoglossal artery must be looked upon as the artery of the IX and X cranial nerves considering that the metameric and branchial arterial systems parallel the development of the nervous system (neural crest). This explains also the connection between the ascending pharyngeal and occipital artery with the VA. For instance, the VA may give rise to the occipital artery or even in case of hypoplasia ends at the occipital artery. The connections between the ascending pharyngeal artery neuromeningeal branch and the third interspace VA branch around the odontoid process must

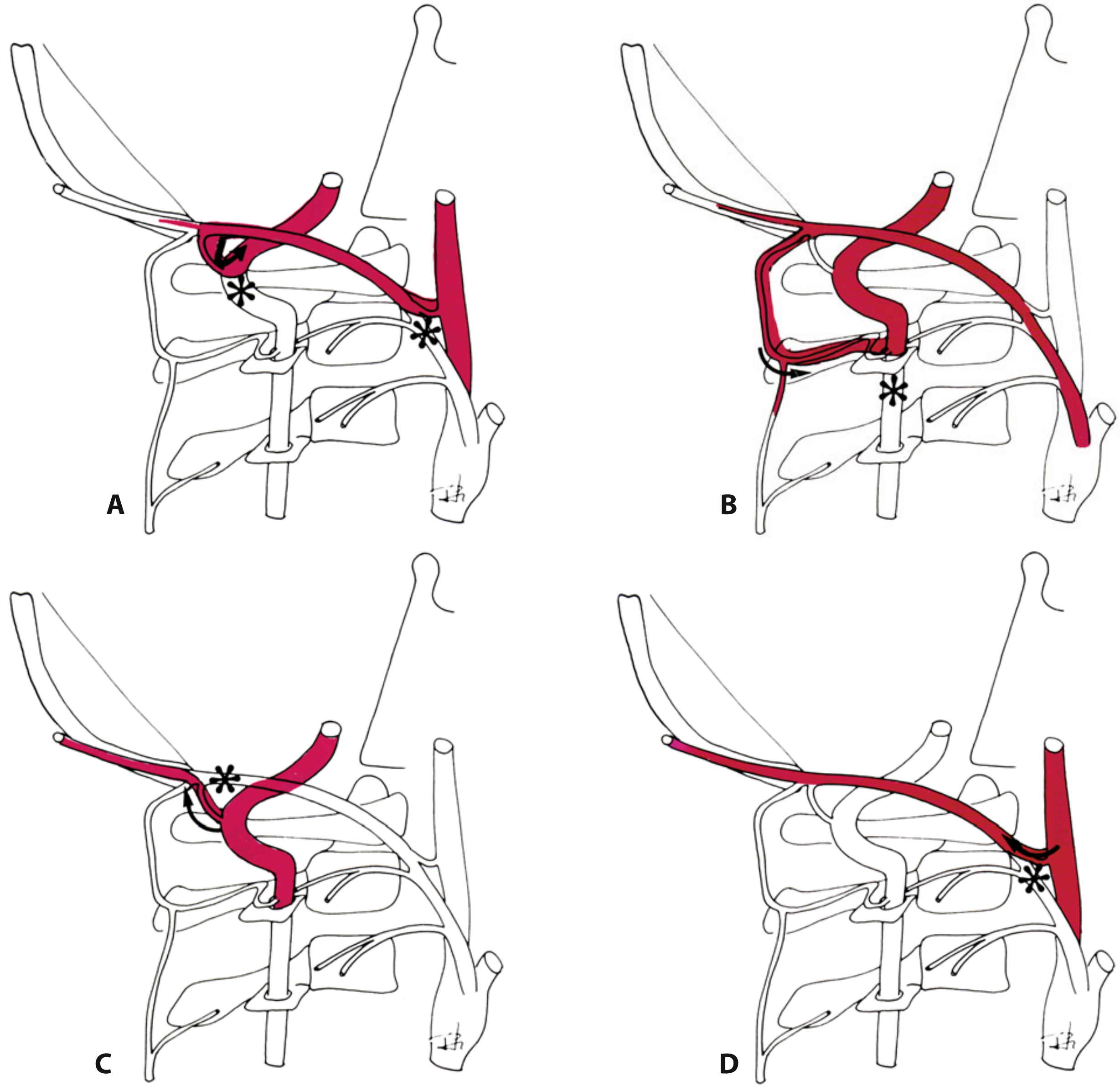

Fig. 4 – Diagrammatic representation of the occipital artery viewed from the side. The *asterisks* represent the site of the vascular regression(s). **A.** The type I proatlantal artery. The basilar sytem originates from the cervical internal carotid artery; it joins the posterior fossa *via* the first cervical space (*broken arrow*). **B.** The type II proatlantal artery. The basilar artery originates from the external carotid artery; it joins the posterior fossa *via* the second cervical space (*curved arrow*). **C.** C1 vertebral origin of the occipital artery (*curved arrow*). **D.** Internal carotid origin of the occipital artery (*curved arrow*). Reprinted by permission from Lasjaunias, P. et al.: The occipital artery. Neuroradiology 15:31-37, 1978.
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also be recalled (Fig. 5). To these connections must be added the branches of the ascending cervical and deep cervical arteries which connect with the branches of the VA at each metameric level; for this purpose it must be specified that the occipital bone is a vertebra which has been integrated into the skull. Therefore, there are eight interspaces and eight cervical nerve roots. The first space is in fact the atlanto-occipital space. These connections, especially between muscular branches named Bosniak's network, are at the origin of the persisting patency of the distal VA in case of proximal occlusion.

The *lateral spinal artery* is an unknown embryonic vessel which usually presents remnant in the adult. It originates lateral to the medulla from either the postero-inferior cerebellar artery (PICA) or the intradural VA, and then courses caudally parallel to the spinal component of the XI cranial nerve, posterior to the dentate ligament. It supplies the XI nerve and the C1–C4 spinal nerves. It anastomoses rostrally with the PICA and with the extradural branches of the VA or the occipital arteries at each metameric level (particularly C2). It ends at the posterolateral spinal arterial axis (Fig. 6). Several variations may be observed from this artery: intradural duplication of the VA at the C1–C2 level, C1 origin of the PICA, C2 origin of the PICA, hypoplastic VA entering the subarachnoid space at C2 (different from the entrance at the foramen magnum), C2 origin of the occipital artery, premedullary duplication of the VA and dual origin of the PICA at C1 and C2 levels.

A corresponding hypoplastic VA can be found for every single instance of enlargement of the lateral spinal artery. Therefore, these variations correspond to

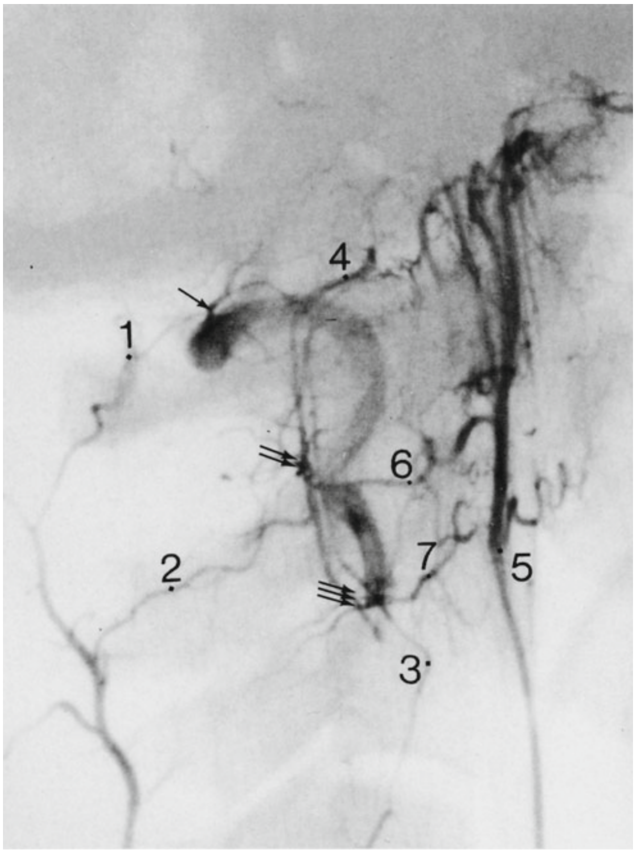

Fig. 5 – Selective injection of the ascending pharyngeal artery. Lateral projection. The indifferent radicular anastomotic arteries are clearly demonstrated; the first (*arrow*), the second (*double arrow*) and the third (*triple arrow*) cervical spaces; 1 and 2: posterior anastomotic channels of the deep cervical artery; 3: ascending cervical artery; 4: upper portion of the odontoid arterial arch system; 5: ascending pharyngeal artery; 6 and 7: anterior radicular anastomotic channels for the second and third cervical spaces. Reprinted by permission from Lasjaunias, P et al.: Arterial supply for the upper cervical nerves and the cervico-carotid anastomotic channels. Neuroradiology 18: 125-139, 1979.

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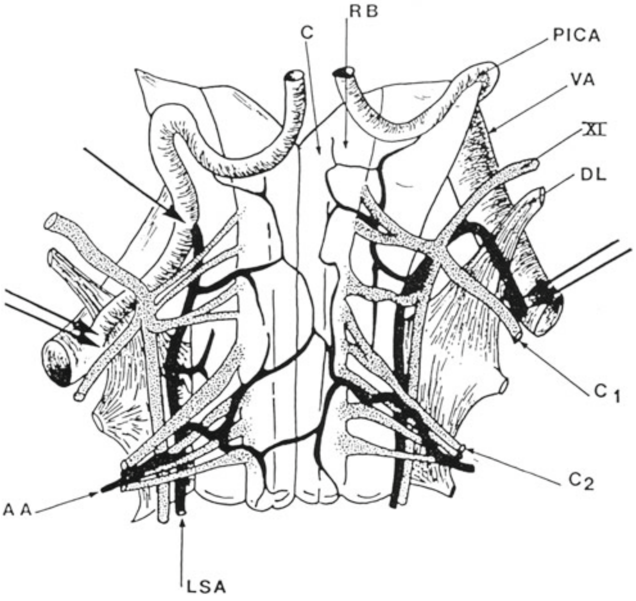

Fig. 6 – Diagram summarizing anatomical relationships of the lateral spinal artery (LSA) at the medullospinal junction. On the left side, the posterior inferior cerebellar artery (PICA) anses (*double arrow*) from the vertebral artery (*VA*), at the level of the C-1 vertebral space; the LSA describes a caudal curve (*arrow*) lateral to the medulla to course dorsal to the dentate ligament (*DL*) and ventral to the posterior root of the first (*C1*) and second (*C2*) cervical nerves. The LSA follows the accessory nerve (*XI*) and supplies the posterior aspect of the spinal cord and medulla up to the clava (*C*) and restiform body (*RB*). On the right side the PICA anses from the intradural vertebral artery rostral to the origin of the LSA.

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a transfer of certain branches of the embryonic lateral spinal artery by a combination of spontaneous regression and persistence of specific arterial channels. Obviously the metameric arteries of the region (first, second and third segmental arteries) play an important role in the persistence of either the *extradural intersegmental anastomosis* (future VA) or the *intradural intersegmental anastomosis* (future lateral spinal artery).

It is of interest to note that none of these variations encountered were associated with parenchymal anomalies at the occipito-cervical junction. These variations illustrate that different equilibrated haemodynamic patterns are able to supply a normally developed nervous system. Similar considerations apply to the relationships between the vertebro-basilar system and the pharyngo-occipital system. The pharyngeal origin of the PICA corresponds to an intermediate stage between a persistent hypoglossal artery and a hypoglossal branch of the ascending pharyngeal system. One can describe intermediate stages between the occipital artery and the VA anastomoses at the C1 level and the type 1 proatlantal artery and between the occipital artery and VA anastomoses at C2 and the type 2 proatlantal artery. The first instance corresponds to the occipital origin of the PICA entering the subarachnoid space at C1 and the second to the occipital origin of the PICA entering at C2. Collateral circulation is a normal function which tries to compensate for a deficient supply. It often develops embryonic arterial systems as though these systems kept the memory of their original role but as tissue differentiation cannot regress, these acquired vascular patterns do not reproduce an embryonic stage.

In some instances the VA has a dual origin: the dominant vessel frequently originates from the thyrocervical trunk or from the aortic arch itself; both arteries enter the vertebral canal and converge at the C4 (or another) level to reproduce the usual aspect of the distal VA. In another case, there is one single vessel which may arise from either of these arteries. In 8% of cases the left VA was found to arise from the aortic arch.

Spinal system

Spinal and spinal cord arteries

The vascular embryology and anatomy of the spine and spinal cord has been well known since the end of the nineteenth century. More recent angiographic works have only confirmed or better defined some specific features (18–27).

In the first weeks of development 31 somites are formed; from the rostral to the caudal end of the embryo, each of these receives one pair of arteries arising from the dorsal aorta: the segmental arteries. These branches course dorsally to supply two groups of territories: bone and muscle derivatives, and neural derivates.

The neural crest receives its arterial supply from a dorsomedial division of the ipsilateral segmental artery (dorsospinal); the central end of the developing nerve will bring the dorsomedial artery branches to supply the neural tube, via paired ventral longitudinal arteries. From these arteries, dorsally orientated vessels penetrate the ipsilateral half of the neural tube in the depth of what will become the ventral fissure. The peripheral end of the developing nerve stimulates the supply to the nerve itself (Fig. 7). Around the neural tube, a network of capillaries will later give rise to dominant paths which rapidly individualize into longitudinal arterial axes. From the sixth week to the fourth month of uterine life, the definitive adult pattern will progressively be formed. Its development occurs in a craniocaudal direction. The two ventral arterial channels of the cord (neural tube) migrate medially and eventually fuse over most of their length to become a single ventral longitudinal

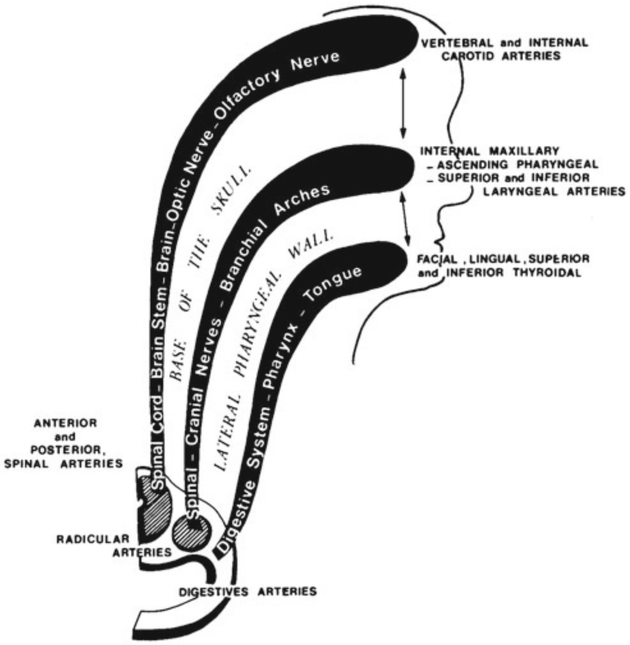

Fig. 7 – Schematic representation of the embryonic development of the neural tube and its arterial supply ; note their cranial homologs. (By permission of Lasjaunias 1986).
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neural axis, the anterior spinal axis. Where this phenomenon does not occur, duplication and fenestration will persist.

Summation and desegmentation lead to regression of the anterior and posterior radicular sources of supply to the ventral axis and pial network: 4–8 anterior radicular arteries (ARA) and 10–20 posterior radicular arteries (PRA) remain (28). The others regress almost completely. The remnants of these segmental branches to the neural derivatives take over the supply to the nerves, bone (extradurally) and dura. This regression is prominent in the caudal region, where a single ARA persists in most instances. Simultaneously, the obliquity of the nerves and the course of the arteries can be recognized, testifying to the growth differences between the spine and the spinal cord (22, 29).

The terminal stages after the fourth month of the embryonic life show an increasing obliquity of the nerve roots and tortuosity of the longitudinal arterial axis until the eighth and ninth months. In the cervical region, the extraspinal longitudinal arteries will be established by persistence of intersegmental anastomoses; these craniocaudal anastomoses will create:

1. the deep cervical arteries dorsal to the transverse processes;
2. the VAs within the transverse processes;
3. the ascending cervical artery (Fig. 8) ventral to the transverse processes.

For this reason the three vessels are potentially involved in the supply to the spinal cord.

The cranial junction of the cord vessels presents interesting developmental features. As previously mentioned, the VA (like the internal carotid artery) cannot be considered as a true vessel since it corresponds to the coalescence and persistence of six consecutive anastomoses between the cervical segmental arteries (Fig. 9). However, the craniocervical portion of the VA corresponds to a true metameric vessel: the proatlantal artery through its proximal origin is not the cervical VA but the proximal ipsilateral occipital artery. Any of the segmental arteries of the craniocervical region represents a possible source of supply to the cervical spinal cord. Therefore, bilateral vertebral angiography alone does not constitute a sufficient screening procedure to evaluate the blood supply to the cervical spinal cord; the cervical and ascending pharyngeal arteries on both sides must be studied to complete the topography of the regional vessels.

In the dogs, the fusion of the paired ventral longitudinal axis collects major radicular contributions at C4–C5. No VA is individualized rostral to that level:

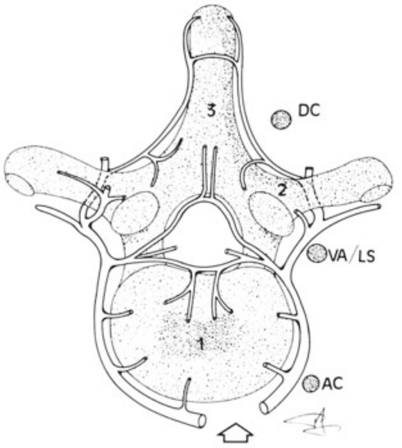

Fig. 8 – Axial view of the arterial supply to the spine. *1,* Vertebral body; 2, transverse process; *3,* spinal process. The three extraspinal dots point to the longitudinal anastomoses between the arteries to the spine. Depending on their level and size these longitudinal anastomoses become: *AC,* ascending cervical artery; *VA,* vertebral artery; *LS,* lateral sacral artery; *DC,* deep cervical artery.
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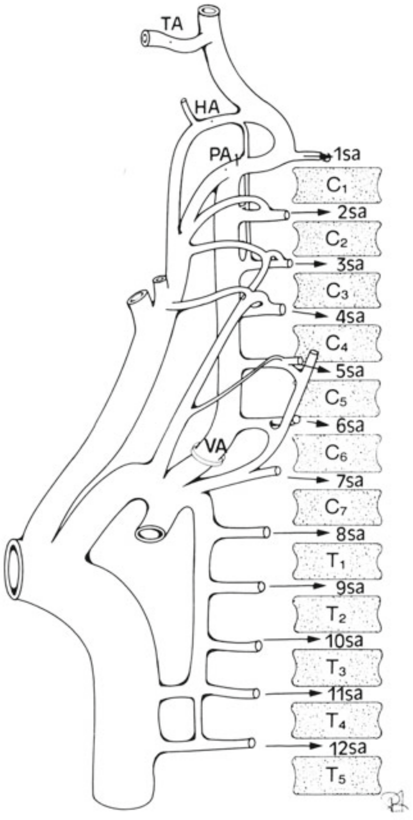

Fig. 9 – Schematic representation of the metameric distribution of the segmental arteries (*sa*) numbered from cranial to caudal; the cervical (*C*) and thoracic (*T*) vertebrae are indicated. Note the carotid (dorsal aortic) origin of the cranial metameric arteries. *TA,* trigeminal artery; *HA,* hypoglossal artery; *PA1,* proatlantal artery, type 1 ; *VA,* vertebral artery (longitudinal anastomosis). (Modified from Padget 1948 and Lie 1968).
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thus, the basilar artery starts at C4 (Fig. 10). In most primates (30) and in humans, anomalies of the anterior spinal axis are frequently observed at the medullary-spinal cord junction (31). The craniocaudally oriented ventral fusion of the longitudinal arteries starts at the circle of Willis. At the craniocervical junction it receives the contribution of the proatlantal (occipito-vertebral) arteries which reverse the craniofugal flow. The proatlantal arteries (or segmental arteries of the C1 nerve) reach the midline to supply the ventral axis and induce a craniopetal flow (the basilar artery). The craniofugal direction persists into the cervical anterior spinal artery. As Gillilan (32) pointed out: 'when both segmental arteries at the same level reach the midline, the ventral longitudinal artery (or anterior spinal artery) takes a diamond shape pattern'. It corresponds to an absence of fusion which can also be seen in the circle of Willis.

Fig. 10 – Ventral view of the cervical spinal cord of the dog. Radiculo-medullary arteries (*double arrows*) join on the midline at the C4 level. Small perforators (*arrow-heads*) penetrate the ventral midline fissure to supply the cervical spinal cord. These radiculo-medullary arteries are homologs of the vertebral artery in man, and this large ascending anterior spinal axis is equivalent to the basilar artery. Note a radiculo-pial artery joining the lateral aspect of the cord (*arrow*).

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The metameric organization of the arterial supply to the cord can therefore be presented as a functionally efficient system that assimilates different tissues with a single source of supply. The link between the spinal cord, spinal nerve, bone, muscle and skin is of interest in the grouping of apparently separate lesions in a single metameric syndrome (33). It must be pointed out that neither the dura mater is involved in these metameric vascular malformations nor does it give isolated congenital arteriovenous malformations. As seen in the cerebral vasculature, the segmental arrangement of the arterial system can be followed intracranially until the trigeminal artery (Fig. 9) which marks the junction between what is called the postsegmental system rostrally and the segmental system caudally.

Spinal arteries

The arterial supply to the spine applies to all the structures derived from the somite, usually with the exception of the corresponding spinal cord territory. The supply is mostly to the muscles of the paraaxial group, the bone and dura. At the cervical level, the longitudinal intersegmental anastomoses have separated the three regions of the vertebra (the vertebral body, the pedicle and the transverse processes, and the spinous processes) so that a given cervical vertebra can actually receive supply from the three different sources on each side (ascending cervical, VA and deep cervical arteries). An additional source of supply at the craniocervical junction concerns the ascending pharyngeal and occipital arteries which represent the remnants of the segmental arteries and supply most of the cranial vertebrae: C1–C2.

In most cases, since each level supplies all the tissue in a given metamere and receives its supply from two segmental arteries at each level (one on each side), each artery supplies approximately half of the vertebral body and muscles of the corresponding metamere. In practice, abnormal blushes during angiography must be correlated with the clinical manifestations to be diagnosed as abnormal. Depending on the quality of the injection (selectivity, amount of contrast and film sequence) reflux through vertebral anastomoses may visualize more than half of the vertebral body without pathological significance. Normal hemivertebral blush is usually homogeneous and well defined, although it may extend beyond the midline; the blush will not bridge the disc spaces.