Gianni Boris Bradac

Applied Cerebral Angiography

Normal Anatomy and Vascular Pathology

Third Edition

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With contributions by Edoardo Boccardi

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Preface

This new edition, titled *Applied Cerebral Angiography*, maintains the same structure of the previous work. There is a part with chapters describing the embryology and normal vascular anatomy, including the orbital and the extracranial sector. This is essential for the correct interpretation of the vascular pathology presented in the second part. This work is completely new: the text has been revised and greatly expanded, trying as far as possible to update the literature. Several new figures and drawings have been added. More attention has been given to the endovascular treatment, considering the increasingly important role played by this type of therapy in the various vascular pathologies. A greater space has been dedicated to ischemic stroke in describing its pathogenesis, the anatomo-pathological and angiographic findings influencing the endovascular treatment, which has become today an essential step in the therapy of this pathology. The new possibilities, positive results, and also the limits of this approach have been largely described and discussed.

We hope that also this new edition will be of practical use for all physicians interested in this field.

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Acknowledgements

The book reflects the work done and the experience gained in the neuroradiological units at the Molinette Hospital of the Turin University, at the Niguarda Hospital in Milan, and at the Santa Croce Hospital in Cuneo. It would not have been possible without the involvement in the daily work of many colleagues working for short or long time in these units. To all these doctors, among them we like especially to mention Prof. Mauro Bergui, Dr. Guido Stura (Turin), Dr. Luca Valvassori (Milan), and Dr. Luigi Gozzoli (Cuneo), as well as to the technicians, nurses, and secretaries we express our sincere thanks. We are also grateful for the collaboration among the members of the anesthesiological, neurosurgical, maxillary surgery, otolaryngology, and stroke units.

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Finally we would like to express our gratefulness for her support to Dr. Ute Heilmann of Springer Verlag and all the editorial team: Mr. Rakesh Kumar Jotheeswaran, Ms. Lizzy Raj, Mr. Claus-Dieter Bachem, Ms. Anna-Lena Buchholz.

Contents

Short Historical Aspects

In July 1927, Prof. Egas Moniz, director of the neurological clinic in Lisboa, presented at the congress of the Neurological French Society in Paris his experiences concerning a method to study the cerebral vessels that he called "*L'encephalographie arterielle*." The interest for this new method, called later "Cerebral Angiography," was great. Among the several neurological authorities present in the congress, we report the comment of Prof. Babinsky:

Le radiographies qui vient de presenter E.Moniz sont remarquables. Si les observations ulterieures établissent definitivement que les injections auxquelles il a recours sont inoffensives,tous les neurologistes seront reconnaissants a notre eminent collégue de leur avoir procuré un nouveau moyen pouvant permetre *de localizer des tumeurs intracraniennes dont le siege est souvent si difficile a determiner.*

Moniz, in the monograph *Die cerebrale Arteriographie und Phlebographie,* published in 1940, reported his further results confirming the diagnostic value of this technique not only in the tumor pathology but also in other pathological processes especially vascular malformations. In the chapter titled "Hirnarteriosclerose" Moniz reported a few cases of occlusion of the carotid artery and of its intracranial branches making the consideration that this pathology is "*selten ,aber doch haufiger als man annehmen moechte … eine sichere Diagnose dieser Affection war vor der Anwendung der Hirnangiographie nicht moeglich*."

Since then, great progresses have been made, starting with the introduction of the catheter technique (Seldinger 1953), the subtraction (Ziedses des Plantes 1963), followed by the development of more and more suitable catheters, guide wires, and less toxic contrast media. All these aspects along with the improved technological equipment have characterized the evolution of the cerebral angiography, which has become a very important neuroradiological diagnostic method opening the way for selective and superselective studies and further for the endovascular therapy.

Certainly, the evolution of new methods such as the angio-CT, angio-MR, and ultrasound allows to replace cerebral angiography in many cases today. However, every time the diagnosis is not sufficiently clear or finer details are required to understand the clinical symptoms or to plan the therapy, especially when an endovascular approach is considered, angiography remains today the method of choice.

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1 Aortic Arch and Origin of the Brachiocephalic and Cerebral Arteries

1.1 Embryogenesis

An important aspect in the embryological development of the cerebrovascular system, as pointed out by Streeter (1918), is that it is not an independent process but it is linked to the progressive development and differentiation of the tissues including the brain parenchyma, its membranes, and the soft tissues of neck and head to which the vascular structure continuously adapts.

The vascular structures develop from primitive vascular arches (Streeter 1918; Congdon 1922; Padget 1948; Barry 1951; Lazorthes 1961; Haughton and Rosenbaum 1974). These are longitudinal vessels developing on each side from a common trunk arising from the heart (truncus arteriosus) which ends in a dilatation (aortic sac) from which arise *the aortic arches*. These have an ascending course forming the primitive ventral (ascending) paired aorta. The vessels then bend dorsally continuing caudally in the paired primitive descending aorta. Both vessels distally fuse together. From these arches arise the brachiocephalic arteries. *In the embryogenesis, six arches in different phases develop and progressively disappear completely or partially*. The first appearing are the arches number one and two which rapidly regress. The third and fourth arches follow. These are the vascular structures which play the most important role in the developing of the brachiocephalic vessels and their future intracranial branches. The fifth arch is not constant. It is frequently incompletely formed, and regresses rapidly after its appearance. From the sixth aortic arch develops the pulmonary artery. In the embryogenesis a vessel (ductus arteriosus) connects each pulmonary artery with the thoracic aorta. This connection closes short after the birth.

The different phases of the development of the extracranial and intracranial cerebral arteries in the embryo have been thoroughly investigated by many authors (Streeter 1918; Congdon 1922; Padget 1944, 1948; Barry 1951; Lazorthes 1961; Arey 1965; Kier 1974; Haughton and Rosenbaum 1974; Lazorthes et al. 1976). A description of this very complex development is summarized, pointing at the more striking aspects considering separately for simplicity, the extra- and intracranial sectors.

At the 4–5 mm stage embryo, approximately 24–29 days of age (Fig. 1.1a), the first and second arches are already completely regressed. The third and fourth arches are developed. From the proximal part of the third arch arises on either side vessels from which develops the future ECA. From its distal part arises the future ICA. The more distal segment of the third arch (ductus caroticus) fuses with the fourth aortic arch continuing on both sides in the dorsal aorta. As described below, connections between ICA and bilateral longitudinal channels (BLA, future vertebro-basilar sector) are present. From the dorsal aorta arise on both sides segmental arteries which contribute later to the formation of the vertebral arteries. In the following stages many changes occur.

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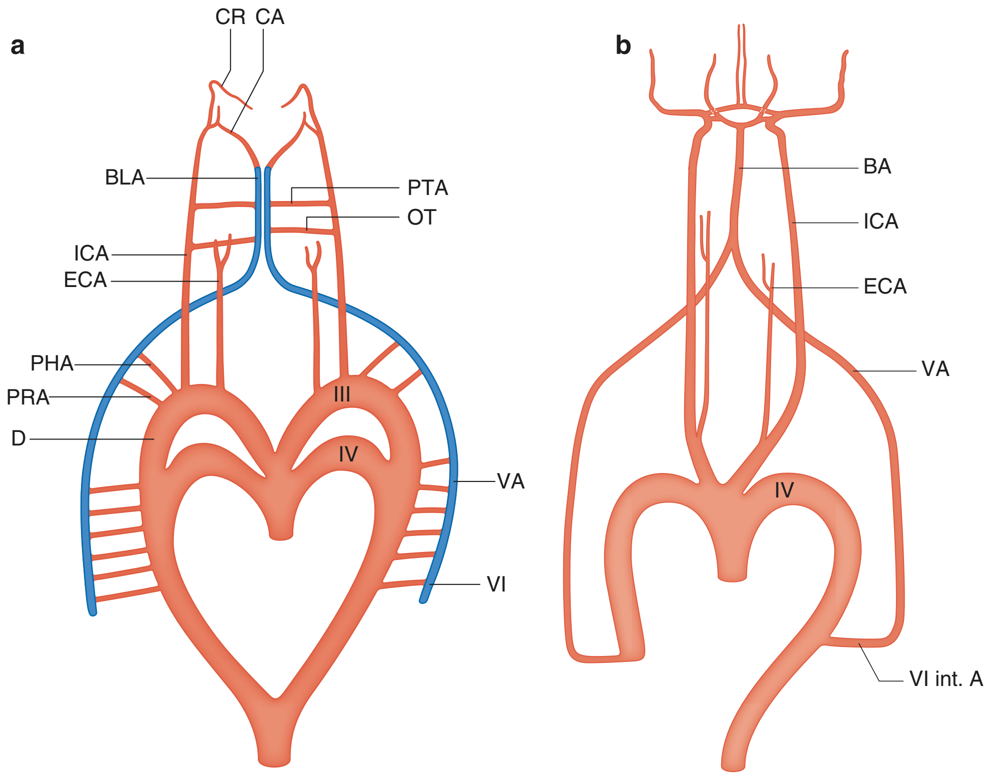

Fig. 1.1 (**a**) Drawing showing the evolution in the early stages (see also text). The first and second arches have already completely disappeared. The ECA arises from the proximal part while the ICA from the distal part of the third aortic arch. Connections between the bilateral longitudinal channels (BLA) and ICA through the trigeminal (PTA) and otic (OT) arteries and between BLA and *ductus caroticus* (D) through the hypoglossal (PHA) and proatlantal (PRA) arteries are present. The *ductus caroticus* connects the third and fourth arches. Intersegmental arteries are connected with a plexiform network from which develop the future vertebral arteries (VA). At this stage, the cranial (CR) and the caudal divisions (CA) of ICA appear. From the caudal division develops the PcomA, which is connected with the distal part of the bilateral longitudinal neural arteries from which develops later the basilar artery. MCA is not developed yet. (**b**) Drawing in advanced evolution (see also text). At this stage, the *ductus caroticus, the hypoglossal, and the proatlantal arteries*, as well *as the trigeminal and otic arteries*, disappear. The right dorsal part of the aorta is regressed. The superior (cervical) intersegmental arteries disappear with exception of the sixth from which arise the vertebral and subclavian arteries. The vertebral arteries (VA) are now developed and connected with the completely formed median basilar artery (BA). The distal branches of the ICA are almost completely formed as well as the circle of Willis. (**c**) Drawing showing the aortic arch and the extra-intracranial cerebral arteries at the end of the embryogenesis. *SA* subclavian artery, *TCT* thyrocervical trunk, *CCA* common carotid artery, *VA* vertebral artery, *ICA* internal carotid artery, *ECA* external carotid artery, *BA* basilar artery. Circle of Willis

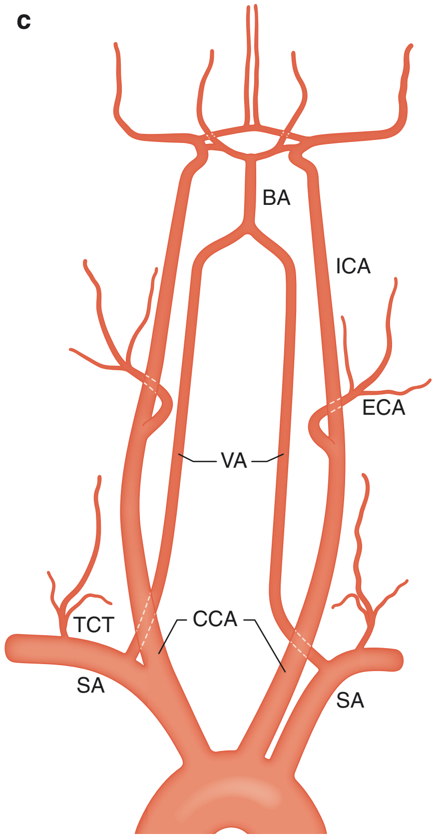

Fig. 1.1 (continued)

At the 20–24 mm stage embryo, approximately 42 days of age (Fig. 1.1b), the anastomoses of the ICA, and ductus caroticus with the BL, disappear (see below). The ECA and ICA arise now as a common trunk, the future common carotid artery (CCA). On the left, the CCA arises from the left fourth aortic arch. From the proximal part of the right fourth aortic arch arises the innominate artery continuing in the right CCA and in the future subclavian artery. The distal part of the right dorsal aorta regresses. On both sides the superior (cervical) intersegmental arteries regress, with exception of the sixth from which develop on either side the subclavian and vertebral arteries (see also Sect. 6.2.4). The more caudally located intersegmental branches become the intercostal arteries.

At this stage the caudal shifting of the heart becomes progressively more prominent leading to further changes of the brachiocephalic vessels. The common carotid artery and the subclavian artery become elongated and progressively located more cranially reaching the adult position. Furthermore the head which is bended ventrally in the first phases of the embryogenesis shifts progressively away from the chest acquiring the typical vertical position.

The final normal aortic arch (Fig. 1.1c) is characterized by the persistence of the left fourth primitive ventral arch from which arise (right to left) the brachiocephalic trunk (innominate artery), the left common carotid artery, and the left subclavian artery. From the brachiocephalic trunk arise the right common carotid artery and the subclavian artery giving off the right vertebral artery. The left vertebral artery arises from the left subclavian artery. Each common carotid artery divides in the external carotid artery (ECA), which supplies the extracranial and meningeal territories and the internal carotid artery (ICA) from which arise the intracranial branches for the cerebral hemisphere and the intraorbital arteries. The vertebral arteries join intracranially the basilar artery. They supply brainstem and cerebellum.

As far as it concerns the development of the intracranial cerebral arteries the most striking aspects are as follows:

1. *At the 4–5 mm stage* (24–29 days of age) (Fig. 1.1a)
   - *Bilateral longitudinal neural arteries (BLA) in the form of plexiform structures develop on the surface of the future brainstem*. The BLA are connected with arteries arising cranially from the ICA (trigeminal and otic arteries) and caudally from branches arising from the ductus caroticus (hypoglossal and proatlantal arteries). The vertebral arteries are in formation. They appear as a plexiform structure arising from intersegmental arteries developing from the dorsal aorta.
   - *There is appearing of the cranial (anterior) and caudal (posterior) division of the ICA*. From the cranial division arises *the anterior choroidal artery* which in this phase of the embryogenesis is well developed

supplying the large choroidal plexus. Opposite to it appear the branches of the primitive ophthalmic artery. More distally develops *the olfactory artery* from which arises a secondary branch, the *anterior cerebral artery*, replacing progressively the regressing olfactory artery. The third branch developing from the cranial division appearing at the 11–12 mm stage (35 days of age) is *the middle* cerebral *artery*. It appears first as a few twigs located between the anterior choroidal artery (AchA) proximally and the developing anterior cerebral artery (ACA) distally. Some of these twigs arise directly from the ACA. From the fusion of these twigs develop the middle cerebral artery.

- From the caudal division arises *the posterior communicating artery* (*PcomA*) *from which emerge* at its distal end a diencephalic branch which includes the medial posterior choroidal and a mesencephalic branch from which arises the lateral posterior choroidal artery. In the further evolution, the PcomA continues in *the posterior cerebral artery* (*PCA*) which progressively extends supplying the posterior part of the cerebral hemispheres. The PcomA (*pars carotica* of PCA) is connected with the cranial part of the bilateral longitudinal neural arteries from which develop the primitive duplicated basilar artery (BA), *which later fuse in the median BA, about the 9 mm stage* (*32 days of age*). The cranial part of these longitudinal channels will become the P1 segment (*pars basilaris* of the PCA). This will becomes progressively the predominant flow to the PCA while the PcomA, in the majority of the cases, partially or completely regresses.
- *The formation of the vertebral arteries progresses and is complete at the 12–14 mm stage embryo (35–38 days of age). They join intracranially the formed basilar artery. The connections of the ICA (primitive trigeminal, otic, hypoglossal, and proatlantal arteries) disappear. The flow towards the posterior circulation which was from cranial to caudal, following the regression of these connections, is now inverted directed from caudal to cranial.*

2. *At the 20–24 mm stage* (Fig. 1.1b) *of the embryonic evolution* (*40–42 days of age*) *the typical cerebral vessels can be identified*. All branches of the ICA are present and clearly recognizable. The development is not complete, since it continues adapting to that of the brain parenchyma.

The growth of the cerebral hemispheres and appearance of convolutions and sulci lead to further distal extent of the arteries and to the changes of the primitive rectilineal course in one more tortuous. The cerebellum develops later. It is supplied by the cerebellar branches arising from the BA and VAs. The development of the vertebral arteries is completed. The VAs are proximally connected with the subclavian arteries and converge cranially to the proximal part of the basilar artery which is now completely formed. From the vertebral and basilar arteries arise the vessels supplying the brainstem and cerebellum. The cerebellar arteries are the latest to develop. *One remarkable development is the formation at the base of the cerebrum of the circle of Willis about the age of 44–52 days of age* (De Vriese 1905; Padget 1944, 1948). This is an anastomotic circle described by Willis in the 1684, and since then called "*circle of Willis*," in which both anterior cerebral arteries are linked by the anterior communicating artery, and each carotid artery is connected through the posterior communicating artery with the respective PCA arising from the basilar artery (Fig. 1.2).

This is a natural well-constructed security system. Its functional value, however, is somewhat unpredictable owing to the many variants present. According to several authors (De Vriese 1905; Padget 1944–1948; Lazorthes 1961; Lazorthes et al. 1976) *the variants of the circle of Willis occur in the postnatal period and through the life due to various hemodynamic changes, among them the compression of the carotid and vertebral arteries by movements of the head and neck.*

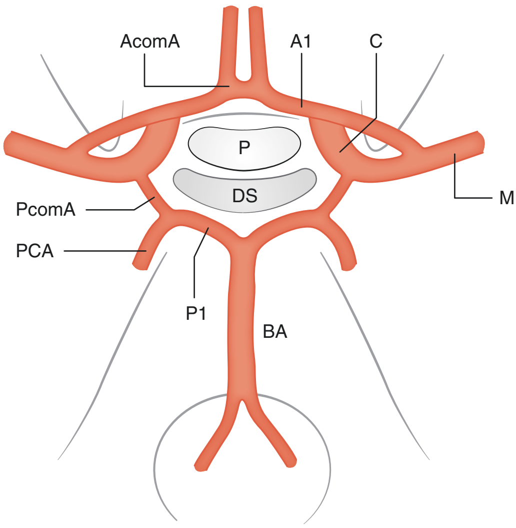

Fig. 1.2 Drawing of the circle of Willis. Internal carotid artery (C), first segment of the anterior cerebral artery (A1), first segment of the middle cerebral artery (M1). *BA* basilar artery, *P1* first segment of the posterior cerebral artery, *PCA* posterior cerebral artery, *AcomA* anterior communicating artery, *PcomA* posterior communicating artery, *P* pituitary gland, *DS* dorsum sellae

1.2 Variants

Some variations of the aortic arch and its branches have already been described in the eighteenth and nineteenth centuries by a few anatomists (Bayford 1789; Tiedermann 1822; Quain 1844; Gray 1859). Angiography, CT angiography, and MR angiography have made possible to demonstrate "in vivo" the great variety of these anomalies, their frequency, and their possible clinical relevance. The progressively better knowledge of the embryogenesis has, furthermore, allowed, at least in some cases, to connect these anomalies with a failure of the normal evolution occurring in specific time of it and involving specific parts of the developing arteries.

Owing to the complexity of the embryonic process, minor variants are the rule. However, these are not recorded in the literature as variants or anomalies. This definition is reserved to more or less complex changes (Adachi 1928; Edwards 1948; Apley 1949; Barry 1951; Lie 1968; Klinkhamer 1969; Haughton and Rosenbaum 1974; Beigelman et al. 1995; Morris 1997; Osborn 1999). In a recent study performed on 2033 patients examined with CT (Mueller et al. 2011), these have been described with a frequency of 13.3% of the cases.

In this chapter are described the variants concerning the aortic arch and the brachiocephalic arteries. Detailed anomalies of the intracranial arteries will be discussed in the specific chapters.

Among the most frequent and more simple anomalies, there are those characterized by the common origin of the left common carotid artery (LC) and the brachiocephalic trunk, and the origin of the LC from the brachiocephalic trunk, instead of arising from the aortic arch. Other variants are the anomalous origin of the left vertebral artery, occurring in about 6% of the cases (Adachi 1928; Uchino et al. 2013b; Mueller et al. 2011) arising from the aortic arch between the left common carotid artery and the left subclavian artery, or more rarely distal to the left subclavian artery. Less frequently, this anomaly involves the right VA, arising from the more proximal segments of the aortic arch or also distal to the left subclavian artery (*vertebral arteria lusoria*). More about the variants of the VAs are described in Sect. 6.2.4.

Among other more complex conditions, there is the right aberrant subclavian artery, arising distal to the left subclavian artery or close to it (*subclavian arteria lusoria*). It is considered to be due to partial persistence of the right dorsal aorta, while its proximal part between the right CCA and the right subclavian artery regresses. It can also be associated at its origin with a small aneurysmal dilatation (Kommerell's diverticulum), perhaps a rudimentary segment of the distal right dorsal aorta. On the aortic arch angiogram the artery appears as the last branch crosses the mediastinum from left to right. Since the first report by Kommerell in 1936 other authors have described this anomaly (Apley

1949; Bosniak 1964; Lie 1968; Klinkhamer 1969; Akers et al. 1991; Freed and Low 1997; Wong et al. 2007; Karcaaltincaba et al. 2009; Uchino et al. 2013b). Another anomaly of the right subclavian artery is that in which the artery arises from the aortic arch separately, proximal to the right CCA. The anomalous subclavian artery can be isolated or associated with other anomalies of the brachiocephalic branches. A frequent association is the common origin of both common carotid arteries and the separate origin of the right CCA proximal to the right subclavian artery. As far as other anomalies concerning the CCA and ICA and VAs see Sects. 2.3 and 6.2.4, respectively.

Extremely rare are other more complex anomalies such as the right aortic arch and the double-aortic arch. In the first case, due to interruption of the left aortic arch at the level of the descending aorta, the brachiocephalic arteries arise from the right aortic arch with a pattern described as a *mirror imaging*. In this condition, from the aortic arch arises (left to right) the left brachiocephalic trunk, which divides distally in the left common carotid and left subclavian arteries, the right common carotid and right subclavian arteries. The left subclavian artery can also arise isolated, distally from the right subclavian artery, appearing on the angiogram as the last branch crossing the mediastinum from right to left. In the double-aortic arch, due to persistence of both arches, commonly each arch gives off a common carotid and a subclavian artery.

Angiographic studies of normal and anomalous aortic arch are presented in Figs. 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, and 1.10.

In the majority of the cases these anomalies are asymptomatic, being discovered during a diagnostic study (angio CT-MR or angiography) performed for a cerebral pathology. However, the possibility of such anomalies should be taken into account by the angiographer. Infrequently, respiratory distress and dysphagia can be present, especially in cases of aberrant right subclavian artery and right VA, due to the course of the vessels, crossing the midline in the retro-esophageal space. Congenital heart malformations can be associated especially with a right aortic arch and double-aortic arch. Furthermore, the knowledge of these variants is important in patients in whom aortic arch, esophageal, or anterior neck surgery is planned.

Some more aspects concerning the embryological development and its abnormalities involving the specific arteries are described later (see Sects. 2.2.3.1, 2.2.3.2, 2.2.3.3, 2.3, 4.3, 5.3, 6.2.4, and 7.5 and Chap. 3).

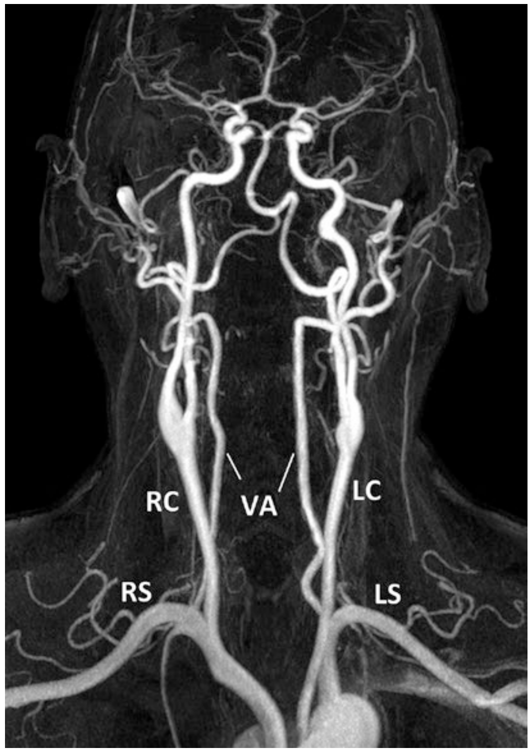

Fig. 1.3 Normal aortic arch, MRI angiography. Brachiocephalic trunk (BR), from which arise the right common carotid (RC) and the right subclavian (RS) arteries. Common left carotid artery (LC), left subclavian artery (LS). Normal origin of both vertebral arteries (VA). That of the right is smaller. The VAs join intracranially the BA. The bifurcation of the two common carotid arteries is well demonstrated as well as the intracranial ICA branches

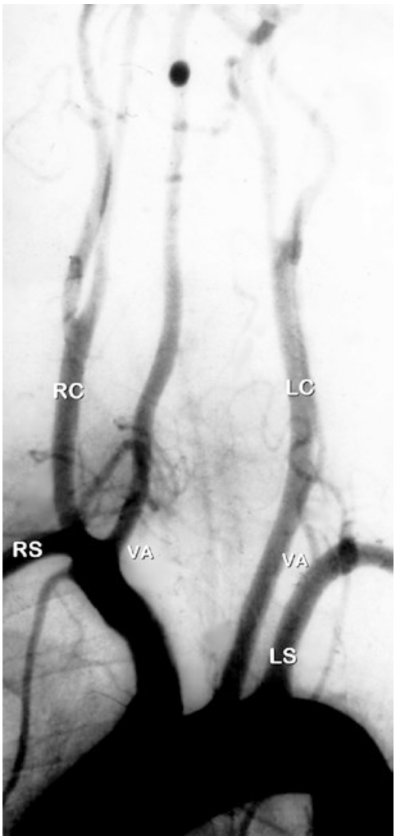

Fig. 1.4 Normal aortic arch angiogram with typical origin of the left and right common carotid arteries (LC, RC). Subclavian arteries (LS, RS). Clear asymmetry of the vertebral arteries (VA). That on the left is hypoplastic

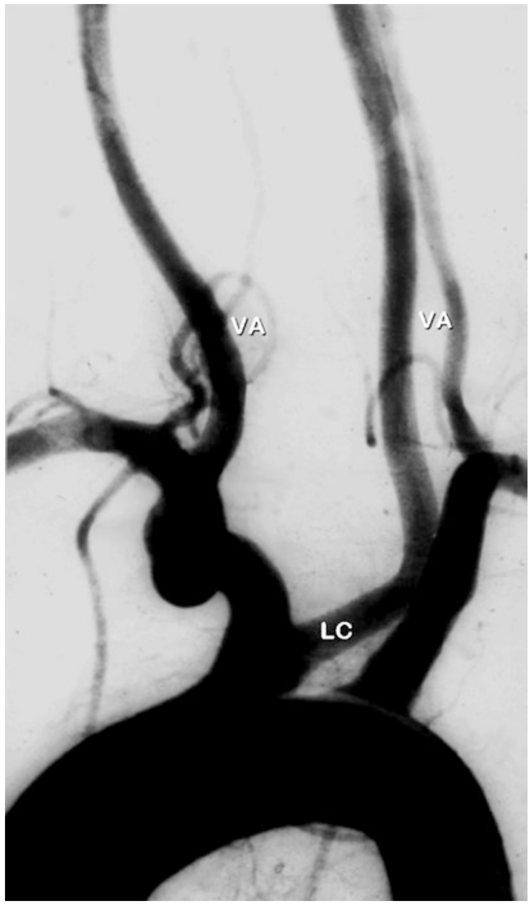

Fig. 1.5 Aortic arch angiogram showing the origin of the left common carotid artery (LC) from the brachiocephalic trunk. The left vertebral artery (VA) is well developed, while that of the right is hypoplastic

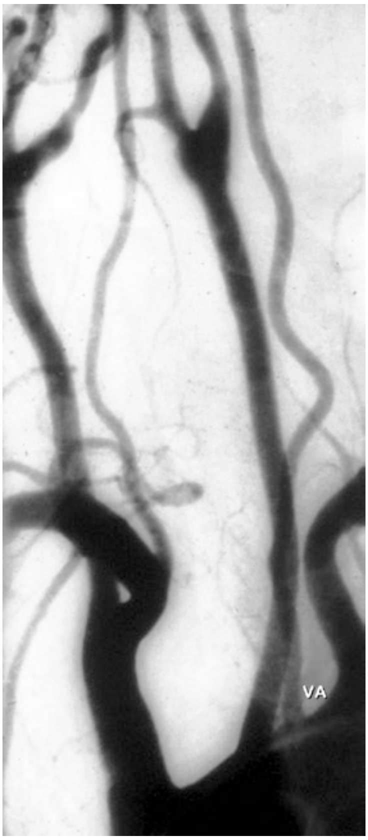

Fig. 1.6 Aortic arch angiogram. Owing to arteriosclerotic elongation of the aortic arch, there is a shifting of the origin of the left common carotid and brachiocephalic trunk towards the heart. Anomalous origin of the left VA (VA) from the aortic arch

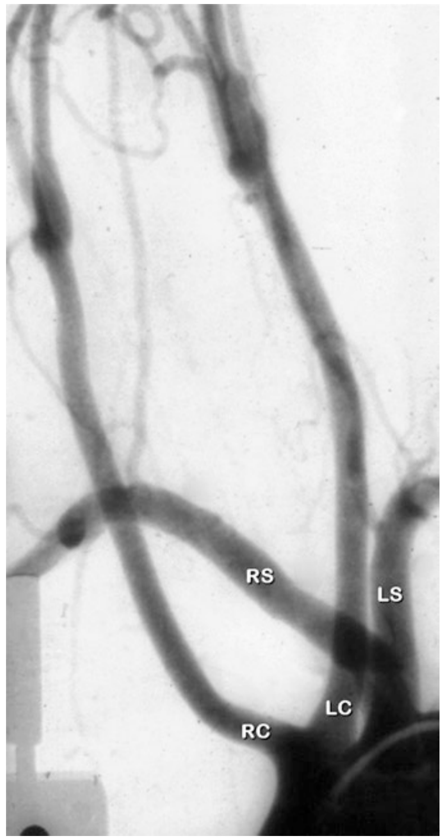

Fig. 1.7 Aortic arch angiogram anomaly. The left and right common carotid arteries (LC, RC) arise as a common trunk. The right subclavian artery (RS) arises distally with a separated or common origin with the left subclavian artery (LS)

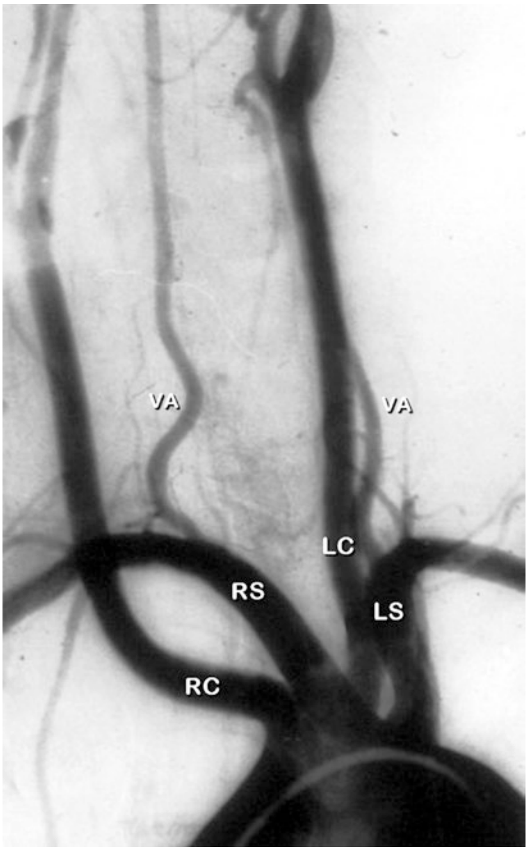

Fig. 1.8 Aortic arch angiogram. The typical brachiocephalic trunk is not formed. The right common carotid artery (RC) is displaced more proximally. It arises from the aortic arch separately from the subclavian artery (RS). This latter arises distally separately or together with the left subclavian artery. Left common carotid artery (LC)

Fig. 1.9 Aortic arch angiogram. The right common carotid artery (RC) arises more proximally. Its origin is separated from that of the right subclavian artery (RS). The typical brachiocephalic trunk is not formed. Left common carotid artery (LC), left subclavian artery (LS)

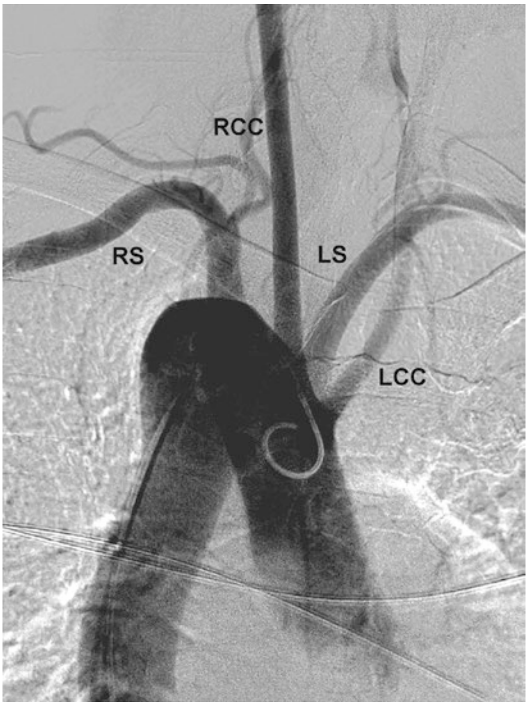

Fig. 1.10 Aortic arch angiogram showing the presence of a right aortic arch. From the ascending aorta arise separately or with a common trunk the left subclavian (LS) and the left common carotid artery (LC). Right common carotid (RC) and right subclavian artery (RS). Pattern which is a "mirror imaging" of the left aortic arch (see also text)

2 Common (CCA) and Internal (ICA) Carotid Artery

2.1 Cervical Segment

Early in the embryogenesis, both primitive proximal external carotid artery (ECA) and internal carotid artery (ICA) arise separately from the third aortic arch: the ECA from its proximal ventral part, and the ICA from the more distal part. The involution of the third aortic arch involving its segment distal to the origin of the ICA (*ductus caroticus*) on both left and right sides results in the formation of a common trunk from which develops on each side the common carotid artery (CCA) continuing cranially in the ICA and ECA. In the further evolution, the left CCA is annexed by the developed left fourth aortic arch, and the right CCA becomes a branch of the brachiocephalic trunk (innominate artery) proximal remnant of the distally regressed right fourth aortic arch (Haughton and Rosenbaum 1974).

The definitive common carotid arteries run cranially in the carotid space, surrounded by the three layers of the deep cervical fascia, called the carotid sheet. Approximately at the level of the hyoid bone, usually between the C4 and the C6 vertebral bodies, each CCA divides into the ICA and ECA.

Cases of a higher bifurcation, up to the first cervical vertebra (Lie 1968), or lower, in the thoracic area (Vitek and Reaves 1973), have been reported. The carotid sheet is a well-defined structure below the carotid bifurcation, though it is incomplete or absent at the level of the oral-nasal pharynx (Harnsberger 1995). The infrahyoid segment of the carotid space contains the common carotid artery and depending on the level of the bifurcation the proximal part of the ICA; the proximal part of the ECA; furthermore the internal jugular vein (IJV); portions of the cranial nerves IX, X, XI, and XII; the sympathetic plexus; and lymph nodes. In the infrahyoid segment, the vessels run in the so-called carotid triangle (Som et al. 2003a) (Fig. 2.1) defined by

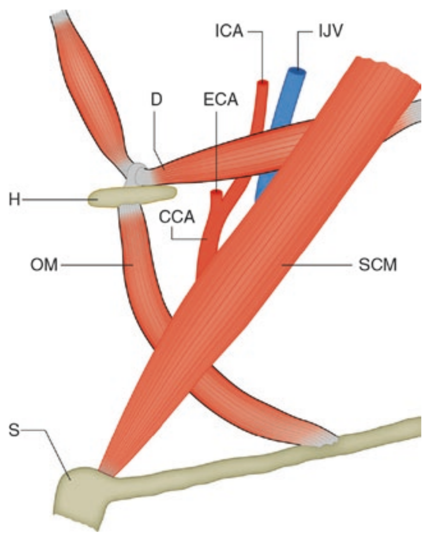

Fig. 2.1 Drawing showing the course of the carotid artery in the carotid triangle. Lateral—oblique view. *SCM* sternocleidomastoid muscle, *OM* superior belly of the omohyoid muscle, *D* posterior belly of the digastric muscle, *H* hyoid bone, *S* sternum, *CCA* common carotid artery, *ECA* proximal external carotid artery, *ICA* infra-suprahyoid segments of internal carotid artery, *IJV* internal jugular vein

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