Functional Vascular Anatomy of the Brain

Michihiro TANAKA[1]

[1]Department of Neurosurgery, Kameda Medical Center, Kamogawa, Chiba, Japan

Abstract

Functional vascular anatomy is the study of anatomy in its relation to the function that figures out the normal and pathological vascularization of the brain and spinal cord. The mechanism of anatomical variations (e.g. fenestration of the basilar artery, persistent primitive trigeminal artery, and aberrant subclavian artery) can be explained according to the embryological development of the cardiovascular system. The most developmental process is common among the species of the vertebrates from the fish to the mammalian in the early phase of embryo. Thus, it is possible to deduce the reasons of vascular variants in terms of phylogeny. Such an embryological parallelism like the comparative anatomy provides the new insights into the nature of our vascular system. In addition, learning more about the hemodynamic consequence may help to realize the underlying physiopathology of cerebral arterial remodeling and stroke in patients with these vascular variants. This perception may facilitate better understanding of the vascular pathologies and lead to the appropriate decision making not only in the diagnostic work, but also in the interventional procedures. The aim of this study is to introduce the meanings of functional anatomy in the clinical application of vascular diseases and anomalous of the central nervous system.

Key words: functional vascular anatomy, embryology, phylogeny, collateral circulation, hemodynamic tolerance, balloon occlusion test

Introduction

Functional vascular anatomy is the study of anatomy in its relation to function that can explain the normal and pathological vascularization of the brain and spinal cord. Collateral circulations and vascular variations affecting the brain can be also explained from the standpoint of the functional anatomy.[1] The knowledge based the functional vascular anatomy is the key to understand the pathoetiology of the cerebrovascular diseases as well as normal variations. There are at least three subjects in the field of functional anatomy. The first is embryological aspect, the second is phylogeny and the third is the ability of adaptation to the certain hemodynamic condition.

History of Functional Anatomy

A famous Scottish doctor John Hunter (1728–1793) was one of the most distinguished scientists and surgeons of his day. He was an early advocate of careful observation and scientific method in medicine. He learned anatomy by assisting his elder brother William Hunter (1718–1783) with dissections in William's anatomy school in London, starting in 1748, and quickly became expert in anatomy.[2]

John Hunter was well known as the discoverer of the collateral circulation via an experiment on stag horns, although the fact that such collateral circulation was already known by his contemporaries. According to some historians, however, it is probable that his recognition of the significance of collateral circulation in preserving the vitality of a deer's antlers after ligation of the external carotid artery may have proved inspirational in his treatment of aneurysms. This was the first discovery and perception of functional vascular anatomy. It is also feasible to visualize the functional anatomy with the medical imaging technology today and this precise visualization gives us a lot of knowledge and insight of the evolution of the vascular system. (Fig. 1)

Modern modalities of neurosurgical intervention have been developed well based on the information technology and knowledge of microanatomy. However, the most pathoetiologies of the vascular diseases on central nervous system are still unknown and have
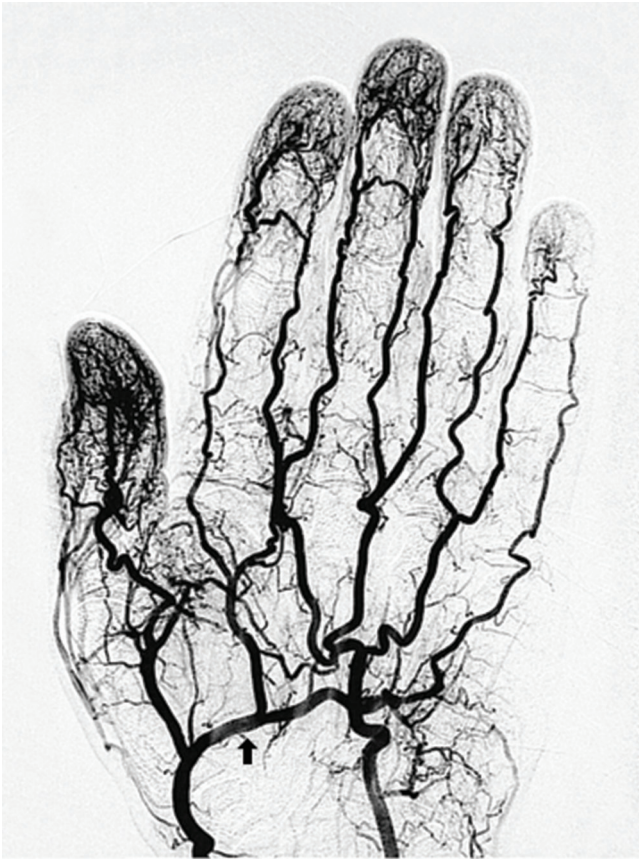
Fig. 1 Angiography of right radial artery. Note there are numerous collateral circulations. Deep palmar arch is a prominent communicating artery between radial artery and ulnar artery. (*arrow*). In each segment of the digit, the anastomosis can be observed between two proper palmar digital arteries. These collateral networks are functioning as the security system for the important organ like a distal segment of the finger. The density of the arterial network on the fingertips of thumb is higher than the little finger. This difference corresponds to the density of the Vater-Pacini bodies on the finger.

not yet been understood well. Three major aspects of functional vascular anatomy are described and reviewed.

Anatomical Variations

Basilar artery embryology and fenestration

The word fenestration refers to a localized or segmental duplication equally to an unfused vessel.[3–5] As well described by Padget, the basilar artery develops from paired primitive longitudinal neural arteries that are formed in the 4–5 mm embryo during the early phase of development. These vessels course longitudinally along the ventral portion of the hindbrain (rhombencephalon) and form focal connections with each other across the midline. As the second

step of development, at five weeks' gestation, fusion of the channels gradually starts to form the basilar artery. When the paired longitudinal neural arteries fail to fuse, fenestration may occur anywhere along the course of the basilar artery.[4] In the literature, the most frequent site of basilar artery fenestration is in the proximal portion (Fig. 2). The middle or distal part of the basilar artery is rarely affected. These data are well corresponded to our results.[4–6]

Formation of Aneurysms

Embryological aspect of ophthalmic artery and the formation of paraclinoid aneurysms

Padget has described the embryology of the ophthalmic artery (OA) in detail through observations of sectioned embryos.[3] According to Padget, a branch of the internal carotid artery (ICA), called the primitive dorsal ophthalmic artery (DOA), emerges in the sequential development of the cerebral arterial vasculature of an embryo/fetus at 4-mm crown-rump length. The orbit consists of three components: first is the retina (peripheral nervous system), second is

Fig. 2 MRA (TOF) showing a lower basilar trunk fenestration. This is the most common variant of the arteries. This fenestration is associated with unfused condition because the basilar artery develops from paired primitive longitudinal neural arteries in terms of functional anatomy.

the optic nerve (central nervous system), and third are the muscles and glands (periorbital structures). The blood supplies to these components reflect their different natures. Lasjaunias et al. revised the theory proposed by Padget to incorporate clinical observations in anomalous variations of the OA.[1] Vascularization of the optic cup was considered as the structures derived from two branches of the primitive ICA, called the primitive ventral ophthalmic arteries (VOA) and the DOA. The VOA arises from the future anterior cerebral artery (ACA), and the DOA arises from the carotid siphon. Later, these arteries anastomose near the optic nerve. The VOA makes an additional anastomosis with the supracavernous portion of the ICA.[1,7,8] Tanaka et al. postulated that the existence of persistent primitive ophthalmic artery might contribute to the formation of paraclinoid ICA aneurysm.[9] (Fig. 3) Indo et al reported that an anomalous origin of the OA was associated with an increased risk of the formation of ICA anterior wall aneurysms.[10] They found ICA anterior wall aneurysms in approximately 25% of ICAs from patients with an anomalous origin of the OA, whereas they were found in only 0.5% of ICAs from patients with a normal OA. This higher frequency of ICA anterior wall aneurysms in ICAs from patients with an anomalous origin of the OA may be due to a failed fusion of the primitive OA in the early embryogenesis, which

Fig. 3 3D rotation angiography showing the paraclinoid aneurysm associated with the intracavernous origin of the ophthalmic artery. It is postulated that there is a relationship between anomalous of ophthalmic artery and formation of paraclinoid aneurysm.

might cause a congenital weakness of the anterior wall of the ICA.[10–12]

These findings of functional anatomy should be considered as the potential risk of visual complication in craniotomy.[13–15] However, persistent ventral and dorsal OAs have been misrepresented in these literatures as abnormal OAs respectively originating from the ACA and the cavernous ICA. Gregg et al. reported that OA arising from the cavernous segment of the ICA derives from a primitive maxillary artery (MA), whereas an OA arising from the ACA represents the partial persistence of a primitive olfactory artery (OlfA); neither corresponds to a persistent primitive OA. This explanation is more accurate and clear that OA originating from the ACA are linked to the partial persistence of a primitive OlfA, whereas OAs arising from the cavernous ICA derive from the lateral branch of the primitive MA.[7]

The true mechanisms of aneurysmal formation are still open, however, it is certain that the concept based on the functional anatomy can be a clue to answer the questions.

Collateral Circulations

Another important aspect of the functional anatomy is the hemodynamic evaluation for the strategy of parent artery occlusion especially in the management of dissecting aneurysm. Prior to the sacrifice of the parent artery, it is necessary to evaluate hemodynamic tolerance.[16] As the functional evaluation of regional cerebral blood flow, a selective balloon occlusion test using a flexible microballoon catheter is reliable.[17] High-quality digital subtraction angiography (DSA), including not only the arterial phase but also capillary and venous phase, can delineate the regional cortical blood flow in detail and collateral circulation through the leptomeningeal anastomosis. If the balloon occlusion test would be applied to the ipsilateral ICA, the microballoon should be placed and inflated exactly at the planning site of occlusion. During this balloon occlusion test, the contralateral injection of carotid artery and vertebral angiography are essential. Digitalized subtraction angiography on anterior-posterior view should be reviewed including not only the arterial phase, but also the capillary and late venous phase.[18] If the both hemisphere of each cortical territory are equally visualized without any delayed opacification, it can be considered with sufficient collateral circulation and judged as the hemodynamically tolerant to the ipsilateral permanent occlusion (Fig. 4).

In 1971, Zülch pointed out that a major cerebral artery occlusion induces a complete reversal of flow
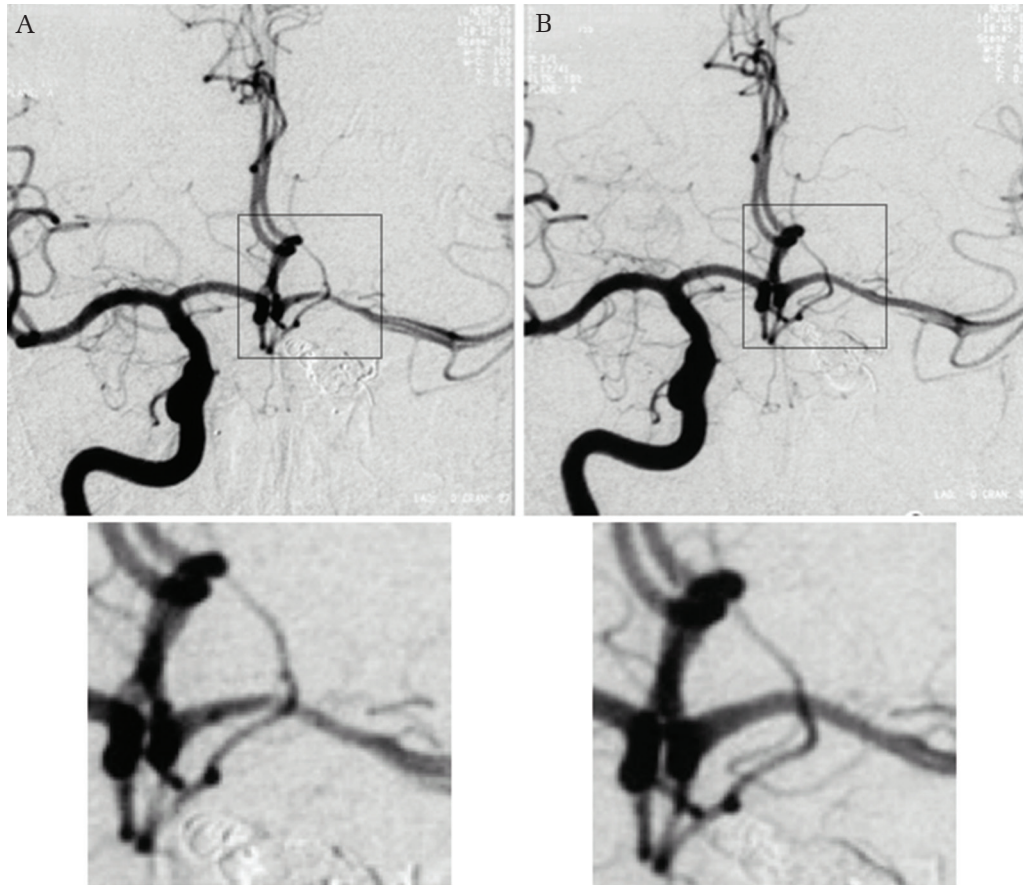
Fig. 4   Right ICA angiography under left ICA balloon occlusion test in the treatment of traumatic carotid cavernous high flow fistula. Immediate after balloon inflation (A) and three minutes after balloon inflation (B). Note the significant dilatation of anterior communicating artery and left A1 segment. This is a phenomenon of immediate adaptation to left ICA occlusion to compensate the hemodynamic compromise in the area of left MCA cortical territory. This functional caliber change is based on the autoregulation of cerebral arteries.

in its branches supplied by the other adjacent two patent arteries.[19]

Case Presentation

A 54-year-old woman presented with sudden onset of headache. An emergency computed tomography (CT) showed an abnormally high density area of a round shape that was measured around 10 mm in diameter, localizing at the left quadrigeminal cistern and pulvinar thalamus. Cerebral angiography showed a dysmorphic fusiform aneurysm at the left P3-P4 segment (Fig. 5A). Because the localization of this aneurysm was close to the tentorial notch, this was considered to be a dissecting aneurysm.[20,21]

Endovascular procedure: Under general anesthesia in the angiography suite, a microballoon was navigated into the P2 segment that was just proximal to this aneurysmal lumen (Fig. 5B). Under inflation of this microballoon, the ipsilateral internal carotid

angiography showed a sufficient collateral supply with retrograde filling of the parieto-occipital branch of the posterior cerebral artery (PCA) (Fig. 5C). Because of this, enough retrograde flow distributing to the distal lumen of the aneurysm, bypass surgery was not indicated in this case.

A 3D-rotational angiography (3D-RA) confirmed that this leptomeningeal anastomosis was mainly supplied from the angular artery of the middle cerebral artery (MCA) (Fig. 6).

The aneurysm and its parent artery were obliterated with platinum coils, and a control ipsilateral internal carotid angiography revealed the complete obliteration of this aneurysm and sufficient collateral flow of PCA cortical territory distal to this aneurysm (Fig. 7). In such a case, it is quite helpful to perform the superselective occlusion test at the level of cortical artery as the functional test of collateral circulations. This technique delineates the leptomeningeal anastomosis between MCA and PCA as the functional
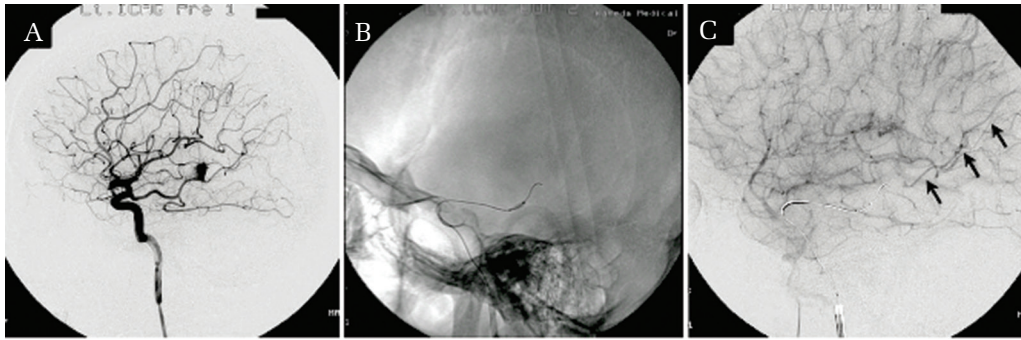
Fig. 5 **(A) Left internal carotid angiography shows fusiform aneurysm locating distal PCA (P3-P4 segment). (B) Through the fetal type of posterior communicating artery, a microballoon catheter was navigated and inflated at the P3 segment that is just proximal to the aneurysm. (C) Left internal carotid angiography under balloon occlusion revealed a retrograde filling of P4 segment through the parieto-occipital branch of PCA. This functional test indicated sufficient collateral circulation through the leptomeningeal anastomosis from MCA cortical territory. It enables the internal trapping of the aneurysm including parent artery without hemodynamic compromise in the territory of PCA.**
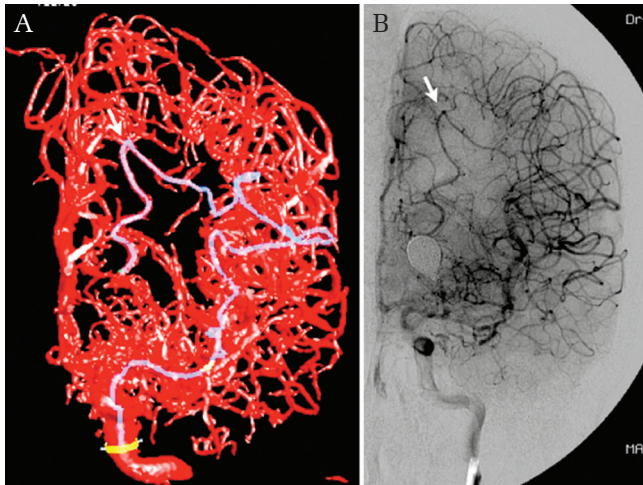

Fig. 6 **(A, B) 3D-RA frontal view corresponding to the DSA showing retrograde filling to the parieto-occipital artery (*arrow*). The use of automated vessel analysis software allows determination of the entire course of the vessel in the region of interest. Note the blue color line on 3D-RA delineating the major collateral pathway of leptomeningeal anastomosis through the angular artery of MCA.**

vascular anatomy, thus provides a lot of information regarding the tolerance to the parent artery occlusion prior to the intervention. The strategy and modality for treatment (e.g. indication of extracranial-intracranial (EC-IC) bypass) can be optimized based on this kind of precise preoperative evaluations.

Conclusions

The functional vascular anatomy is the key to understand the various types of vascular variations.
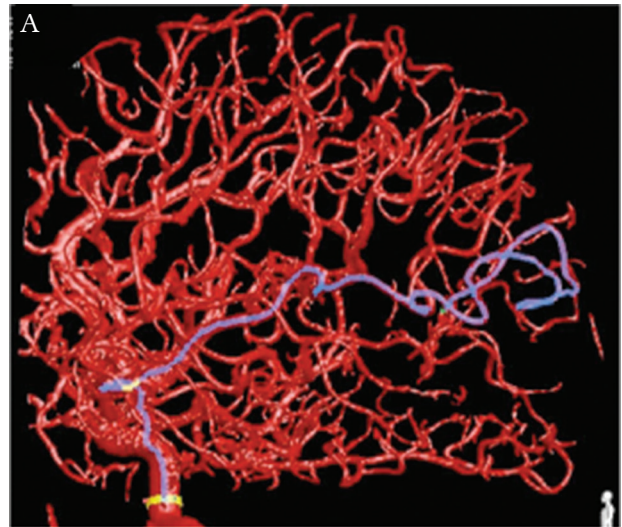
Fig. 7 **3D-RA lateral view (A) and the schematic representation by Zülch (B) demonstrating the potential anastomosis at the level of the cortical artery.**

It is quite effective to provide the optimal strategy in terms of surgical neurointerventions. Many mechanisms of the vascular pathology might be explained with the theory of functional vascular anatomy associated with the embryology.

Conflicts of Interest Disclosure

I declare that I have no conflict of interest.

References

1) Lasjaunias P, Berenstein A, ter Brugge KG: Clinical Vascular Anatomy and Variations. Berlin, Heidelberg, Springer Berlin Heidelberg, 2001
2) Sloffer CA, Lanzino G: Historical vignette. Dominique Anel: father of the hunterian ligation? *J Neurosurg* 104: 626–629, 2006
3) Padget DH: The development of the cranial arteries in the human embryo. *Contr Embryol* 32: 205–261, 1948
4) Tanaka M, Kikuchi Y, Ouchi T: Neuroradiological analysis of 23 cases of basilar artery fenestration based on 2280 cases of MR angiographies. *Interv Neuroradiol* 12 (Suppl 1): 39–44, 2006
5) Black SP, Ansbacher LE: Saccular aneurysm associated with segmental duplication of the basilar artery. A morphological study. *J Neurosurg* 61: 1005–1008, 1984
6) Gailloud P, Albayram S, Fasel JH, Beauchamp NJ, Murphy KJ: Angiographic and embryologic considerations in five cases of middle cerebral artery fenestration. *Am J Neuroradiol* 23: 585–587, 2002
7) Gregg L, San Millán D, Orru' E, Tamargo RJ, Gailloud P: Ventral and Dorsal Persistent Primitive Ophthalmic Arteries. *Oper Neurosurg* 12: 141–152, 2016
8) Bracco S, Gennari P, Vallone IM, et al.: Double ophthalmic arteries arising from the internal carotid artery: a case report of a hidden second ophthalmic artery. *Surg Radiol Anat* 38: 1233–1237, 2016
9) Tanaka M: Persistent primitive dorsal ophthalmic artery associated with paraclinoid internal carotid artery aneurysm. *J Neuroendovasc Ther* 3: 39–41, 2009
10) Indo M, Oya S, Tanaka M, Matsui T: High incidence of ICA anterior wall aneurysms in patients with an anomalous origin of the ophthalmic artery: possible relevance to the pathogenesis of aneurysm formation. *J Neurosurg* 120: 93–98, 2014
11) Hassler W, Zentner J, Voigt K: Abnormal origin of the ophthalmic artery from the anterior cerebral artery: neuroradiological and intraoperative findings. *Neuroradiology* 31: 85–87, 1989
12) Li Y, Horiuchi T, Yako T, Ishizaka S, Hongo K: Anomalous origin of the ophthalmic artery from the anterior cerebral artery. *Neurol Med Chir* (*Tokyo*) 51: 579–581, 2011
13) Louw L: Different ophthalmic artery origins: Embryology and clinical significance. *Clin Anat* 28: 576–583, 2015
14) Kadooka K, Tanaka M: Ophthalmic systems completely supplied from dural arteries indicate the utility of endovascular treatment of cerebral aneurysms. *Interv Neuroradiol* 21: 765–768, 2015
15) Uchino A, Saito N, Kurita H, Ishihara S: Double ophthalmic arteries arising from the internal carotid artery. *Surg Radiol Anat* 35: 173–175, 2013
16) Zülch KJ: Angiographic findings on the pathogenesis of cerebrovascular disorders. *Zentralbl Neurochir* 31: 1–25, 1970
17) Tanaka M, Maekawa H, Sakata Y, Obikane Y, Hadeishi H, Yamazaki A: Role of bypass surgery and balloon occlusion test for the endovascular management of fusiform dissecting aneurysms. Report of two cases. *Acta Neurochir Suppl* 119: 43–48, 2014
18) Théron J, Nelson M, Alachkar F, Mazia D: Dynamic digitized cerebral parenchymography. *Neuroradiology* 34: 361–364, 1992
19) Zülch K: Cerebral circulation and stroke. In Zulch KJ (ed): Berlin/Germany, Springer, 1971
20) Drake CG, Amacher AL: Aneurysm of the posterior cerebral artery. *J Neurosurg* 30: 468–474, 1969
21) Chong WK, Lee SK, Terbrugge KG: 3T MRI - 3D DSA fusion technique on posterior cerebral artery dissecting aneurysm: understanding a potential pathophysiologic mechanism. *Interv Neuroradiol* 12: 215–221, 2006

Address correspondence to: Michihiro Tanaka, MD, PhD, Department of Neurosurgery, Kameda Medical Center, Higashi-cho 929, Kamogawa, Chiba 296-8602, Japan.
e-mail: michihiro.tanaka@gmail.com