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Review

The embryologic basis for the anatomy of the cerebral vasculature related to arteriovenous malformations

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ABSTRACT

A detailed understanding of vascular anatomy is essential to facilitate appropriate decision-making by clinicians responsible for treating arteriovenous malformations (AVM) of the brain and dura. This work reviews the embryologic development of the cerebral vasculature, including the dural venous sinuses, with a focus on the relevant angioarchitecture. There is little doubt that dural AVM are acquired lesions; however, conflicting evidence exists regarding the pathophysiology of brain AVM. Patients described in this review provide support for both of the proposed mechanisms for the development of brain AVM (post-natal development compared to embryologic origin). Further work is required to improve our understanding of the pathophysiology of these lesions.

1. Introduction

Traditional theories regarding the congenital etiology of cerebral arteriovenous malformations (AVM) are being challenged, and are being replaced by more comprehensive pathophysiological hypotheses that AVM occur as a result of an active angiogenic and inflammatory response to some post-natal inciting vascular event.[1–5] In contrast, there is little doubt that dural AVM are acquired lesions, although the precise mechanisms involved in the pathogenesis of a dural AVM remain unclear. It is likely that the pathogenesis of a dural AVM involves a complex interaction between pro-angiogenic and anti-angiogenic factors, leading to a dynamic process involving the recruitment of pre-existing physiological arteriovenous shunts located within the dura mater.[6,7] Venous sinus thrombosis may be a precipitating event,[8,9] or may occur subsequent to the development of a dural AVM.

Imaging modalities, particularly diagnostic subtraction angiography, provide a detailed appreciation of the angioarchitecture of individual AVM of the brain and dura, allowing surgical and endovascular treatments to be tailored to specific requirements. A detailed understanding of the vascular anatomy is essential to facilitate appropriate decision-making by clinicians responsible for treating these lesions. This paper reviews the embryologic basis for the anatomy of the cerebral vasculature, including the dural venous sinuses.

2. Anatomy

2.1. Meninges

The cranial meninges consist of the dura mater, arachnoid and pia mater. The arachnoid and pia are collectively referred to as the leptomeninges. The dura mater is composed of an outer periosteal layer and an inner meningeal layer, and together these are referred to as the pachymeninges.[10,11]

2.2. Dura mater and dural venous sinuses

The outer layer of dura is firmly adherent to the inner table of the skull, and is essentially the periosteum of the skull. It does not extend below the foramen magnum, and as such does not participate in the continuation of the dura mater around the spinal cord; nor is it invaginated by the cranial nerves.[12] The inner layer of dura is the meningeal dura, and represents the true dura mater. Although the inner layer is firmly attached to the outer layer of dura in most places, it folds upon itself to form several dural reflections, which constitute the falx cerebri, falx cerebelli, tentorium and the diaphragma sellae.

At the edges of the dural reflections (both the attached edges and, to a lesser degree, the free edges) the dural layers are separated to form venous channels – the dural venous sinuses. These venous sinuses are lined by endothelium, and are held open by the fibrous nature of the dura mater. Together, the dural venous sinuses drain virtually the entire brain.

The dural venous sinuses can be anatomically classified into two groups: (i) an antero–inferior group, consisting of the

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cavernous sinus, intercavernous sinus, sphenoparietal sinus, superior petrosal sinus, inferior petrosal sinus and basilar plexus; and (ii) a superior–posterior group, consisting of the superior sagittal sinus (SSS), inferior sagittal sinus, straight sinus, transverse sinus (TS), sigmoid sinus and occipital sinus.[13,14] The confluence of the SSS, left and right TS and straight sinuses is often called the confluence of venous sinuses, or "torcula herophili".[15] All of the dural venous sinuses drain towards the sigmoid sinuses, and then extracranially via the jugular veins. A small amount of venous blood bypasses the dural venous sinuses, and is directed extracranially through the veins of the posterior fossa via the vertebral venous plexus, or through a series of diploic and emissary veins.[16]

2.3. Function of the meninges

The dura mater serves several functions. Its primary function is supportive, providing mechanical support to the brain within the various dural compartments through its intimate attachment to the arachnoid (and thus, to the pia mater).[12,17] It also provides an additional protective layer, particularly in the setting of skull fracture following trauma. The periosteal layer of dura provides nutrients to the overlying skull, and the dural venous sinuses provide a network of venous drainage for the entire brain. The dura may also have an important role in the fusion of cranial sutures in the infant.[18]

The arachnoid has an important role in permitting flow of cerebrospinal fluid (CSF) through the subarachnoid space and cisterns, as well as being the principal site of reabsorption of CSF into the venous circulation through the arachnoid villi. Through its attachments to the overlying dura and the pia mater, it provides support to the brain.[12,17] The CSF that circulates through the subarachnoid space and CSF cisterns bathes the brain and provides buoyancy. The arachnoid also performs a barrier function, acting as an impermeable membrane between the CSF within the subarachnoid space and the dura mater.[10]

The pia provides the mechanism that allows the dura mater to support the brain through its intimate attachment over the contours of the brain. A sleeve of pia follows each blood vessel as it enters or leaves the brain, creating the perivascular spaces within the brain (Virchow–Robin spaces).[11,17]

2.4. Arterial anatomy

A detailed description of the cerebral arteries is beyond the scope of this review; however, Rhoton has expertly described the arteries of the supratentorial space and posterior fossa in his comprehensive publications.[19,20]

The arterial anatomy of the dura is less well described. Meningeal arteries, with a diameter of 400 μm to 800 μm, supply the dura. The main meningeal arteries divide into a rich network of primary anastomotic vessels that lie on the periosteal surface of the dura, with a diameter of 100 μm to 300 μm. These primary anastomotic arteries anastomose widely with other anastomotic arteries, and freely cross the midline through the SSS. They divide into four smaller arterial units – the arteries to the skull, secondary anastomotic arteries, penetrating vessels and arteriovenous shunts. A rich capillary network (diameter 8–12 μm) is also present within the dura (Table 1).[21,22]

Branches of the external carotid artery (ECA), internal carotid artery (ICA), the vertebral artery (VA) and the basilar artery (BA) supply the cranial dura mater.[23] The regional arterial supply of the dura mater is summarised in Table 2. Exceptional instances of additional dural arterial supply have been reported, including the occurrence of cervical branches of the thyrocervical trunk sup-

Table 1
Microvasculature of the dura mater

Arterial unit	Diameter (μm)	Description
Primary anastomotic arteries	100–300	Lie on the periosteal surface of the dura, widely communicating with other anastomotic arteries
Arteries to the skull	40–80	Pass through tiny foramina on the inner aspect of the cranium
Secondary anastomotic arteries	20–40	Lie on the outer dural surface; freely anastomose with each other in a regular polygonal network
Penetrating vessels (arterioles)	40–50	Leave the outer dural surface to extend to within 5–15 μm of the juxta-arachnoid surface; terminate in a rich capillary network
Arteriovenous shunts	50–90	Located within the midportion of the dura
Capillaries	8–12	Rich network of capillaries within the dura

Table 2
Regional arterial supply of the dura mater

Regional dura	ECA supply	ICA supply	VB supply
Skull vault	Anterior and posterior division of MMA		
Skull base	Ascending pharyngeal artery; MMA; occipital artery	Meningohypophyseal and inferolateral trunks; ethmoidal and anterior frontal meningeal branches of ophthalmic artery	Posterior meningeal and anterior meningeal arteries (from VA); subarcuate artery (AICA)
Falx cerebri	Paramedial arcades from MMA	Anterior falcine arteries from ethmoidal artery; medial tentorial branch of cavernous ICA (to posterior falx); pericallosal branch of ACA (to free edge of falx)	Posterior meningeal artery; tentorial branch of PCA (to posterior falx)
Superior surface of tentorium	Posterior temporal, paramedian and petrosquamosal branches of MMA; ascending pharyngeal artery; occipital artery	Medial (marginal) tentorial and lateral (basal) tentorial branches of cavernous ICA	Posterior meningeal artery; tentorial branch of PCA
Inferior surface of tentorium	Ascending pharyngeal artery; occipital artery		Tentorial branch of PCA; posterior meningeal artery; anastomotic branch of BA
Posterior fossa	Jugular and hypoglossal branches of ascending pharyngeal artery; mastoid branches of occipital artery; branches from MMA	Clival branches of dorsal meningeal artery (from cavernous ICA); dorsal meningeal artery (meningohypophyseal trunk)	Anterior and posterior meningeal branches of VA; dural branches of VA; subarcuate artery (AICA)

ACA = anterior cerebral artery, AICA = anterior inferior cerebellar artery, BA = basilar artery, ECA = external carotid artery, ICA = internal carotid artery, MMA = middle meningeal artery, PCA = posterior cerebral artery, VA = vertebral artery, VB = vertebrobasilar artery.