Neurosurg Rev (2015) 38:253–264
DOI 10.1007/s10143-014-0590-2

REVIEW

Cranial dural arteriovenous shunts. Part 1. Anatomy and embryology of the bridging and emissary veins

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Received: 9 May 2014 / Accepted: 22 June 2014 / Published online: 3 December 2014

Abstract We reviewed the anatomy and embryology of the bridging and emissary veins aiming to elucidate aspects related to the cranial dural arteriovenous fistulae. Data from relevant articles on the anatomy and embryology of the bridging and emissary veins were identified using one electronic database, supplemented by data from selected reference texts. Persisting fetal pial-arachnoidal veins correspond to the adult bridging veins. Relevant embryologic descriptions are based on the classic scheme of five divisions of the brain (telencephalon, diencephalon, mesencephalon, metencephalon, myelencephalon). Variation in their exact position and the number of bridging veins is the rule and certain locations, particularly that of the anterior cranial fossa and lower posterior cranial fossa are often neglected in prior descriptions. The distal segment of a bridging vein is part of the dural system and can be primarily involved in cranial dural arteriovenous lesions by constituting the actual site of the shunt. The veins in the lamina cribriformis exhibit a bridging-emissary vein pattern similar to the spinal configuration. The emissary veins connect the dural venous system with the extracranial venous system and are often involved in dural arteriovenous lesions. Cranial dural shunts may develop in three distinct areas of the cranial venous system: the dural sinuses and their interfaces with bridging veins and emissary veins. The exact site of the lesion may dictate the arterial feeders and original venous drainage pattern.

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Keywords Bridging vein · Emissary vein · Dural arteriovenous fistula · Dural arteriovenous shunt

Introduction

The bridging veins (BVs) derive from the embryonic pial-arachnoidal veins and connect the pial veins with the dural sinuses or plexuses. The emissary veins (EVs) on the other hand represent the remaining connections of the superficial venous system with the dural venous system during the development of the skull. Cranial dural arteriovenous fistulae (CDAVF) are often anatomically related to the bridging and/or emissary veins of the brain, but their exact relation is not clear.

Although the embryology and anatomy of the cerebral bridging and emissary veins has been studied to some extent, standard descriptions are often incomplete and frequently neglect veins particularly in the region of the anterior skull base, the anteromedial middle fossa, and the lower posterior fossa. In neuroanatomical textbooks, the bridging veins of the brain are not presented as a separate entity and the most prominent ones are studied in the context of the group they belong to, i.e., the superior superficial veins in relation to the superior sagittal sinus or the vein of Galen in relation to the deep venous system [1, 2]. Classic works on embryology of the cerebral venous system [3–6] constitute our standard sources of information. In more recent publications, prominent bridging veins in specific locations have been analyzed with regard to their interface with the sinuses from an anatomic and histologic point of view [7–10]. Typically, traumatic injuries that cause tearing of the bridging veins have been a subject that attracted attention to these vessels [11–15]. Indeed, most publications on the anatomy of the bridging veins are from the neurosurgical literature, since the study of its detailed anatomy is central to many surgical approaches [16–27].

However, all bridging and emissary veins, regardless of location and group, share a common anatomical and functional characteristic, i.e., the connection of the cerebral venous system with the dural sinuses-plexuses and the extracranial venous system, respectively. Bridging veins may be primarily involved in CDAVF with direct cortical venous drainage, whereas emissary veins can also be involved [28].

This report reviews the anatomy and embryology of the cerebral bridging and emissary veins focusing on aspects that may help to better understand dural arteriovenous disease.

Materials and methods

Relevant English-language articles on the anatomy and embryology of the bridging and emissary veins were identified using one electronic database (PubMed). Publications having the keywords "bridging vein" and "emissary vein" in their title were considered potentially relevant. We found 47 and 31 publications about bridging veins and cranial emissary veins, respectively, which were supplemented with data from reference texts and selected German-language and Italian-language articles. A review of the embryology and topographic anatomy of the BVs and EVs is presented.

Of the 47 publications on the intracranial bridging veins, 13 focused to surgical anatomy and neurosurgical approaches; 12 were anatomic, histologic, or imaging studies; 9 were related to traumatic injuries; 9 were related to their physiology and properties; 1 was a review; and 3 were related to the BVs as drainage routes of dural arteriovenous shunts. Of the 31 publications on the emissary veins, 12 were anatomic studies, 11 were related to their pathology and physiology, 6 were related to surgery, and 2 were in relation to dural arteriovenous shunts.

Over the years, there have been various schemes for the classification of the cerebral venous system. In this report, we combined the terminology of the embryological literature [5, 29] that refers to the territory of BVs with the anatomic-topographic terminology [30–32], which mostly refers to the dural exit of the veins.

Results

Embryology of the bridging and emissary veins

The venous system of the head is subdivided into three separate systems: the superficial system serving the integument and soft parts, the dural system lying between the dura and bone, and the cerebral system. All three are originally outgrowths of the same capillary plexus which by the end of the fourth week (5 to 8 mm embryo), surrounds the neural tube, and drains by means of an anastomosing venous plexus forming the so-called dural plexuses [3, 33].

These plexuses, together with an intervening smaller venous mesh, which connects them more or less completely, drain the neural tube dorsolaterally and converge into the primary head-sinus. Schematically, the anterior dural plexus drains the telencephalon, diencephalon, and mesencephalon; the middle dural plexus drains the pons and cerebellum; and the posterior plexus drains the medulla.

By the sixth week, the layers of the meninx primitiva are demarcated and multiple anastomoses among the pial veins are formed in parallel with the process of "cleavage of blood vessels" described by Streeter [3] by which the numerous short veins of the deeper, pial meningeal layer which drain into the abovementioned plexuses convert into larger connections between the regions of the developing neural tube and the venous sinuses of the more superficial, dural layer. These are the so-called pial-arachnoidal veins, the future bridging veins. In other words, after this cleavage process, the primary head-sinus and its three tributary plexuses become established as a true dural system, distinguished from the deeper "cerebral veins" belonging to the leptomeningeal system. These two systems connect with each other through the bridging veins.

During the seventh week, at least one pial-arachnoidal vein can usually be identified for each of the five regions of the primitive brain: the telencephalic, mesencephalic, and metencephalic veins in addition to the veins from the diencephalon (ventral or inferior diencephalic) and myelencephalon (myelencephalic), identifiable already during the fifth week. Since the definitive veins emerge as augmented remnants in the reduction of many short pial-dural connections, variation in their exact position and number is the rule [3].

By the eight week, the development of the cranium separates the superficial venous system, which drains the muscles and skin, from the dural system. This separation process starts first in the lower parts of the head where the superficial system matures earlier and has the form of a plexus that gradually spreads upward over the vault. The emissary veins constitute the remaining anastomoses between these two systems [3]. The emissary veins of the hypoglossal canal appear first whereas the parietal emissary veins are formed last [6].

Ventral and dorsal telencephalic territory

By the end of the seventh week, the telencephalic vein (the future fetal tentorial sinus), which drains the primordial striatum, empties into the caudoventral aspect of the marginal sinus (future transverse sinus), whereas tributaries of the anterior and middle plexus are forming the tentorial plexus (the future torcular) [6].

The beginning of the superior sagittal sinus appears in embryos about 14 mm long, whereas in embryos 50 mm long, it is partially established and receives a number of tributaries that are variable in location and size, remnants of the anterior dural plexus. These tributaries correspond to the superior superficial BVs.

Diencephalic territory

The ventral diencephalic vein lies on the hypothalamus and initially drains into the head-sinus. Later, the ventral diencephalic vein annexes the drainage of the choroid plexus of the lateral ventricles and often the dorsal diencephalic vein, which normally drains the more posterior dorsolateral aspects of the primitive thalamus into the transverse sinus. Finally, its distinct exit to the tentorial sinus in most cases is lost and becomes a part of the system of the basal vein. It accepts also pial tributaries, which are anastomosed with tributaries of the lateral telencephalic (future superficial middle cerebral) vein; a process that leads to the formation of the medial telencephalic vein (future deep middle cerebral vein) [6].

Mesencephalic territory

In the embryo, the mesencephalon is actually drained by a dorsal vein on either side, the dorsal mesencephalic vein, whereas a ventral vein occasionally appears connected via collateral veins of the lateral mesencephalic and/or the ventral metencephalic network with the basal and galenic system. The fate of the dorsal mesencephalic, which initially drains into the tentorial plexus and future transverse sinus, is not completely clear. Its distal part may disappear or being annexed by the superolateral cerebellar hemispheric venous system as it moves more caudal and lateral during development, due to the enlargement of the cerebellum and the shift of the transverse sinus [34]. After the 15th week of gestation, the mesencephalic draining veins are exclusively connected to the superior venous system of the posterior fossa either through the lateral mesencephalic to the basal vein or through the precentral vein to the galenic vein.

Metencephalic territory

There are often two (dorsal and ventral) metencephalic veins.

The ventral metencephalic vein often annexes tributaries of the dorsal metencephalic, when present, to form one conspicuous stem, the superior petrosal vein, which empties into the superior petrosal sinus (SPS).

Myelencephalic territory

In Padget's description about the fate of the primitive myelencephalic vein, it is stated that the stem of this pial-arachnoidal vein, lying between the roots of the ninth and tenth nerves, gives origin to the inferior petrosal sinus (IPS).

Anatomy of the bridging veins

Superior cerebral BVs

This group includes the veins from the superior part of the medial and lateral surfaces of the cerebral hemispheres from the frontal lobe anteriorly to the occipital pole posteriorly. Han et al. [9] described and compared cadaveric with angiographic findings in this area and found an average of 11 BVs draining into the superior sagittal sinus (SSS) on each side. They found that venous lacunae did not directly receive the BVs whereas some BVs drained into the meningeal veins before entering the sinus. Vignes et al. [10] studied the junctions between the superior BVs and the SSS and found that the diameter of the BVs increases just before opening into the sinus, and the collagen fibers at the junctions have a different orientation and a myoendothelial junction organized as a real "sphincter." A recent publication by Chen et al. advocates a similar concept [35] (Fig. 1).

Middle cranial fossa BVs

In this group, BVs connected to the sinus of the lesser sphenoid wing, the cavernous sinus, or venous remnants of the floor of the middle fossa are included [36]. Despite the controversy whether the superficial sylvian vein empties into the sinus of the lesser sphenoid wing (the so-called sphenoparietal sinus) or directly into the cavernous sinus [30, 37–39], its final segment constitutes a bridging vein draining either into one of the above sinuses or occasionally into the sphenobasal or sphenopetrosal sinuses [30].

In addition to the above prominent and well-described BVs, there are also the often-neglected [40] anterior temporal BVs, which often empty into the sinus of the lesser sphenoid

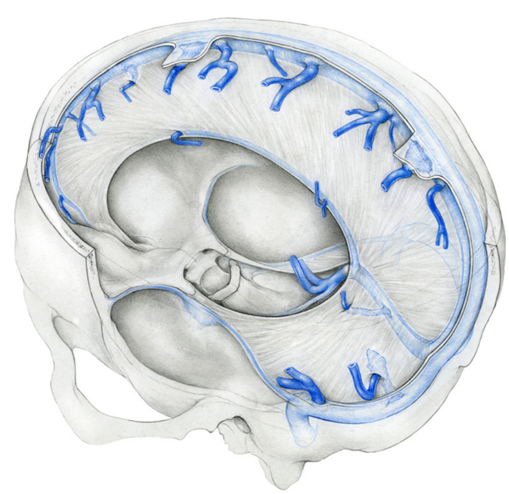

Fig. 1 Schematic illustration focusing on the superior cerebral BVs, medial and lateral, connected to the superior sagittal sinus and the BVs of the inferior sagittal sinus. The galenic BV is also illustrated

wing [38, 41]. Other BVs of the floor of the middle fossa, which empty into remnants of the anterior segment of primitive tentorial sinus and smaller veins draining the inferior surface of the temporal lobe, bridging the dura at the petrous pyramide region have been also described [41] (Fig. 2).

Superior tentorial BVs

In this group belong the cerebral bridging veins, which drain the lateral surface of the temporal lobe and the basal posterior surface of the temporal and occipital lobes either directly into the superior aspect of transverse or to the tentorial sinuses [42] or superior petrosal sinuses. There is an average of eight bridging veins per side draining into the transverse sinus [25]. These veins usually converge coursing around the inferior edge of the hemisphere to reach the sinus. The vein of Labbé is part of this group [43]. Sakata et al. [44] studied the dural exits of the temporal BVs and according to their definitions found a transverse sinus exit in 52 %, a tentorial exit in 23 %, and a petrosal one in 25 % of cases. The tentorial sinuses can empty in the straight sinus, torcular, transverse or superior petrosal sinus [45], or in more than one sinus, thus functioning also as an anastomotic channel [46]. The adult tentorial sinus probably represents one of several possible persisting patterns of the fetal tentorial sinus [32]. The terminal segment of a vein emptying into a tentorial sinus corresponds to a BV (Fig. 3).

Anterior cranial fossa

The veins, draining the orbital surface of the frontal lobe, can be divided into the anterior ones (anterior orbito-frontal and fronto-polar veins), which empty into the superior sagittal sinus, and the posterior ones (posterior orbito-frontal and olfactory veins), which drain backward to join the basal vein. The anterior orbito-frontal vein drains the anterior part of the

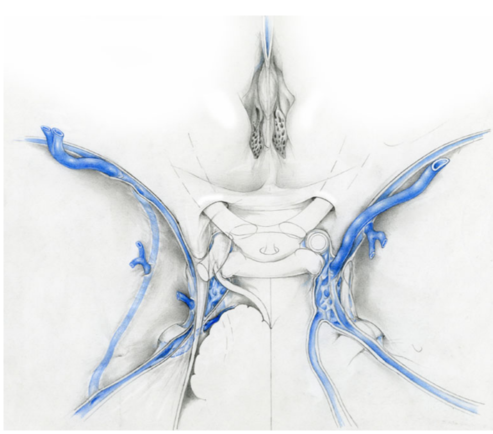

Fig. 2 Schematic illustration focusing on middle fossa BVs, connected to the cavernous sinus, sinus of the lesser sphenoid wing, and superior petrosal sinus. The uncal BV is also illustrated

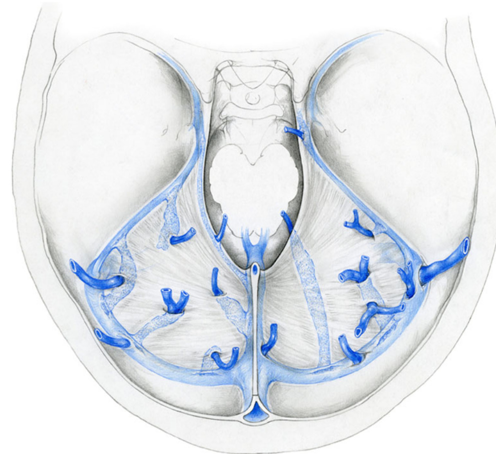

Fig. 3 Schematic illustration focusing on the superior tentorial BVs and showing some of the many possible venous anatomic configurations, not necessarily coexisting in one individual

gyrus rectus and the anteromedial part of the orbital gyri; the posterior orbito-frontal veins drain the posterior portion of the orbital surface of the frontal lobe; and the olfactory vein drains the olfactory sulcus and the adjacent part of the gyrus rectus and medial orbital gyri [30].

In anatomic studies, no BVs or emissary veins of the floor of anterior cranial fossa are typically described. When the foramen cecum is patent, it may transmit a vein connecting the nasal cavity to the SSS. Tenchini in 1905 has observed an abnormal "orbito-frontal emissary vein" which passed from the superior longitudinal sinus of the brain through the roof of the orbit to join the superior ophthalmic vein [47]. Parese in 1960 referred to a fronto-polar vein showing communication with the angular vein of the face in an angiographic image [41]. A few cases with angiographic demonstration of a vein penetrating rather at the level of the lamina cribrosa and draining the nasal mucosa into the SSS have been recently described [48].

In old and new anatomical textbooks, the drainage of the nasal cavity is described as superiorly through ethmoidal veins, which pass through the cribriform plate into the venous plexus of the olfactory bulb or directly into one of the veins on the orbital surface of the frontal lobe of the brain [49–51]. Additionally, due to the lack of valves in the veins of this area, a bidirectional flow is possible [52]. Lang described that the veins of the anterior ethmoidal canal and posterior ethmoidal canal drain in an extracranial direction in 16 and 12 % of cases, respectively [53] (Fig. 4).

Falcine BVs

This group is composed of the veins that drain the cingulate gyrus and corpus callosum into the inferior sagittal sinus

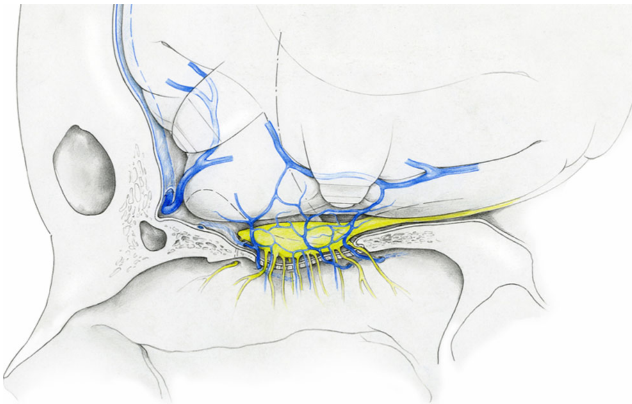

Fig. 4 Schematic illustration of the venous exits in the ethmoidal area, anterior to and at the lamina cribriformis. Notice the direct duro-leptomeningeal venous connections at the level of the olfactory bulbs, as well as the BV exiting at the lowermost end of the superior sagittal sinus

through the anterior pericallosal veins, as well as the parahippocampal, paraolfactory, paraterminal gyri, uncus, anterior part of the calcarine fissure, and deep venous system (striatal, diencephalic, and choroidal veins) to the straight sinus through the internal cerebral, basal, and great veins.

As a collector vein, the basal vein is the result of secondary longitudinal anastomoses of the deep telencephalic vein, the ventral diencephalic vein, the mesencephalic vein, and also the dorsal diencephalic tributary of the internal cerebral vein or the superior mesencephalic tributary of the vein of Galen, after elongation and attenuation of the tentorial sinus due to posterior expansion of the cerebral hemispheres [54]. Typically, it drains posteromedially to join the vein of Galen, which is a major BV. However, there have been described several variations. For instance, opening of the basal vein into the anterior, middle or posterior portion of the straight sinus, or into the transverse sinus [1, 5, 54] either directly or indirectly via a tentorial sinus. Bridging veins from the basal vein or the peduncular vein to a sinus coursing in the tentorial edge [30, 45] or to the cavernous sinus [1] have been also described (Fig. 3). Direct connection of the superficial middle cerebral vein with the basal vein has been also reported, but such a constellation is described in only a single case and appears not related to the dural system [55]. In the case of failure of anastomosis between the first and second segment of the basal vein, a prominent uncal vein draining into the cavernous or paracavernous sinus may be observed. Such an uncal vein would be a bridging vein draining the anteriormost tributaries of the basal vein into the cavernous sinus (Fig. 2).

Galenic or superior group of the posterior fossa

Here belong the mesencephalic tributaries, which may join the basal vein, the petrosal vein, the transverse pontine vein, and the precentral vein, but typically, they do not open directly into a specific mesencephalic-bridging vein. Also, the superior vermian and precentral veins, which drain the tectal area, the superior vermis, and the superior part of the cerebellar hemispheres anterior to the fissure prima, typically empty into the galenic system and not independently into the straight sinus [1, 56].

Petrosal BVs or anterior metencephalic group

The tributaries of the superior petrosal vein, namely the vein of the great horizontal fissure, the brachial vein, the vein of the lateral recess of the fourth ventricle, the lateral pontine vein, and the transverse pontine vein, which drain the anterior brainstem and cerebellum, empty into the superior petrosal sinus. In some cases, these tributaries may form separated bridging stems, which drain into the SPS independently [54, 57] (Fig. 5).

The transverse pontine vein or the anteromedial pontomesencephalic veins often empty also separately into the cavernous sinus or the basilar plexus [1]. Kiyosue et al. [58] found a bridging vein connecting the transverse pontine vein to the posterior aspect of the cavernous sinus in 94 % of their cases and bilaterally in half of them (Fig. 6).

Inferior tentorial BVs or dorsal metencephalic group

Here belong the inferior vermian veins and the superior and inferior lateral hemispheric cerebellar veins. The inferior vermian BVs with its tributaries run posterosuperiorly in the paravermian fissure and empty into the straight sinus, torcular, or transverse sinus, either directly or indirectly through a tentorial sinus. The hemispheric bridging veins are formed

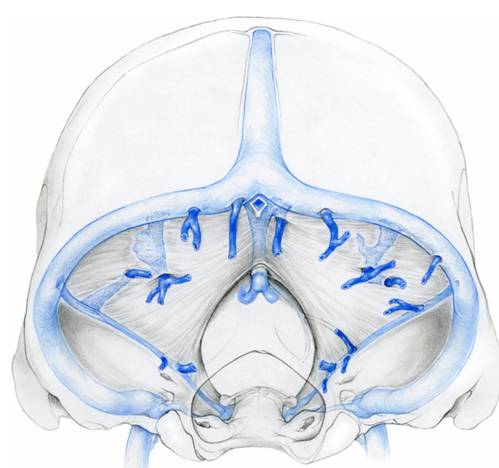

Fig. 5 Schematic illustration displaying the inferior tentorial BVs, including the petrosal BVs as seen from a caudal view. It shows some of the many possible venous anatomic configurations, not necessarily coexisting in one individual

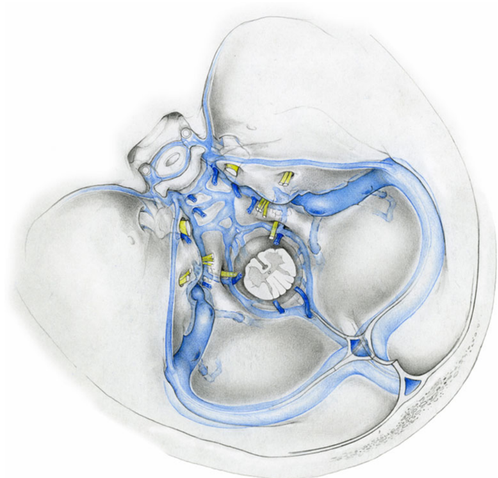

Fig. 6 Schematic illustration displaying the BVs of the posterior fossa as seen from above and left, after removal or the tentorium. It shows some possible venous anatomic configurations, not necessarily coexisting in one individual

either by the union of superior and inferior hemispheric veins or by the union of superior hemispheric veins only or inferior hemispheric veins only and drain frequently into a tentorial sinus or directly into the transverse sinus [20]. In a few cases, an inferior vermian or hemispheric vein give rise to a bridging vein which drains into the occipital sinuses below the torcular [59]. Choroidal veins can drain the plexus of the fourth ventricle into the occipital dural plexus [56] (Fig. 5).

Medullary BVs

In the literature, the medullary bridging veins as a separated group have been described as "other" infrequent bridging veins [31]. Here belongs the inferior petrosal vein, which is formed by the vein of the pontomedullary sulcus and other lateral medullary veins and drains between the ninth and tenth nerve into the inferior petrosal sinus [1] or alternatively into the sigmoid sinus [31, 59]. The medullary veins at and below the level of the pontomedullary sulcus give rise to bridging veins to the inferior petrosal sinus near the jugular bulb in 8–14 % of cases, to the distal sigmoid sinus in 37 %, and to the marginal sinus in 9–42 % of cases [58, 59]. These bridging veins can be topographically connected with specific parts of the exiting sinus as with the veins in the hypoglossal canal [31, 59]. Small bridging veins from this level can empty also into the distal occipital sinus [56, 59]. Similarly, Duvernoy, by describing the so-called satellite veins of the cranial nerves, referred to the lateral medullary vein found in more than 30 % of cases, which accompanies the XI nerve and empties into the sigmoid sinus. He described also the inferior transverse medullary vein emptying either through a vein running along the roots of the hypoglossal nerve to the anterior condylar vein found in 8 % of cases, or through a vein running along the anterior root of first cervical nerve found in 32 % of cases, or to the marginal sinus. The posterior aspect of the medulla is drained either upward through the lateral medullary veins or downward through a vein of the cerebellomedullary cistern to the marginal sinus, or to both directions [1] (Fig. 6).

In addition to the above-described locations, several atypical BVs may be encountered in diagnostic angiograms [60].

Emissary veins

According to the definition of emissary veins in Gray's anatomy, "they are veins which pass through apertures in the cranial wall and establish communication between the sinuses inside the skull and the veins external to it" [50]. The cranial nerves that cross concrete cranial apertures (all except the VIII nerve) are accompanied by at least one small or larger emissary vein except the facial and the olfactory nerves, whose accompanying veins do not fulfill the criteria of typical emissary veins according to the above definition due to the lack of connection with a sinus.

The described emissary veins grouped according to the sinus they are connected to are as follows:

1. The mastoid emissary vein connected to the sigmoid sinus, and the posterior condylar vein connected to the distal sigmoid sinus [5, 61, 62]. The jugular bulb has also been considered a major emissary vein since it connects the sigmoid sinus with the internal jugular vein through the jugular foramen [63].
2. The network of veins in the hypoglossal canal connecting the marginal sinus and the anterior internal vertebral plexus and basilar plexus with the anterior condylar confluence and through it with the jugular bulb and the distal extracranial inferior petrosal sinus.
3. The emissary veins of the middle fossa through the foramen ovale, rotundum, lacerum, Arnold, and Vesalius, all connected to the cavernous sinus [32]. In this group, also the ophthalmic veins are included since they are considered emissary veins connecting intracranial to extracranial veins. The (distal) inferior petrosal sinus has also the position and function of an emissary vein connecting the cavernous sinus with the jugular vein [32]. Part of this group is also the inferior petro-occipital vein connecting the carotid venous plexus with the anterior condylar confluence or the superior jugular bulb and running almost parallel to the inferior petrosal sinus [61, 64]. Some authors have described clival EVs connected to the basilar plexus [65].
4. The parietal emissary vein and the vein of the foramen cecum when patent, both connected to the SSS. Rare presence of fronto-frontal or orbito-frontal emissary veins connected to the SSS has also been described [66]. At the

level of the anterior cranial fossa, lamina cribrosa, no emissary vein has been described.
5. The occipital emissary vein can be connected either to the torcular, transverse sinus, or the occipital sinus.
6. A temporal emissary vein may connect the remnant of the petrosquamosal sinus with the deep temporal vein. The superficial petrosal vein has been described as an EV connecting the accompanying vein of the greater petrosal nerve in the floor of the middle cranial fossa with the accompanying vein of the facial nerve in the stylomastoid foramen [67]. Here, however, the criterion of connection with a sinus is missing.
7. The meningo-orbital vein connecting the middle meningeal vein/sinus or its remnant with the orbital venous system, usually the lacrimal vein [63].

A characteristic of the emissary veins is that they drain also diploic veins [63].

Discussion

All BVs as derivatives of the pial-arachnoidal embryonic veins and being essentially pial-arachnoidal-dural connectors are anatomically and by definition, superficial veins despite their description according to various classifications of the cerebral venous system as deep (i.e., vein of Galen) or superficial [30].

Lasjaunias et al. describes the BVs as “transdural veins” [68] and the BVs of the brainstem under the name of “emissary veins” or “emissary-bridging veins” aiming apparently to display homologies with the spinal venous anatomy [32, 69]. In fact, for the spinal cord, where there are no sinuses, the term “bridging-emissary vein” describes the anatomy accurately. For the cranial area (with the exception of the lamina cribriformis, which we will discuss further down), we did not clearly find a similar anatomic configuration, either around the brainstem or elsewhere. Therefore, we preferred to strictly use the terms that describe the veins avoiding a mixture of two structures (BVs and EVs) with different embryology, anatomy, and function.

Padget in her description of the myelencephalic pial-arachnoidal vein hypothesized that it corresponds to the adult inferior IPS without mentioning any real adult bridging vein. It might be that the inferior petrosal vein, which is a bridging vein at the level of the ninth and tenth nerves draining into the IPS corresponds to the above pial-arachnoidal vein.

As was shown also by Padget and confirmed by subsequent studies, the largest veins on the pial surface of the adult brain traversing the arachnoid to enter the dura are superficial to the arteries and particularly in their distal segment belong more to the dural than to the pial layer [6, 70]. Histological studies have shown that fascicles of collagenic and elastic fibers of the superior sagittal sinus incorporate with the adventitia of the BVs, which at the distal segment is also formed by numerous and voluminous fascicles of collagenic fibers and thin elastic fibers, arranged in spirals within the venous wall [71]. Dagain et al. in their study of the junction of BVs with the transverse and tentorial sinus found the BVs with muscle cells and “dural reinforcement” [8]. Other histological studies concerning the junction of the great vein with the straight sinus have been controversial. Velut et al. and Ruchoux et al. reported the existence of dural septa and dural arterial supply of the distal vein of Galen and histology of a transitional venodural nature [72, 73], whereas Dagain et al. in their study found the great vein to be a “true vein” with smooth muscle fibers [74]. The BVs are closely attached to the inner dural surface and have a shorter or longer intradural course before they enter the sinus [75].

Therefore, from the embryological point of view but also in the adult anatomy, the distal BV segment, veno-sinusal junction, appears to belong to the dural system. This implies that an arteriovenous dural shunt can be primarily located on a bridging vein and that the BV involvement in a dural shunt may not be restricted only to the role of carrying the refluxing blood into the cerebral venous system (leptomeningeal venous drainage (LVD)) [76, 77]. In such a case, the venous reflux to the cortical venous system would be direct without interposition of a sinus. Moreover, in case of thrombosis of the BV’s exit to the sinus, the shunt venous drainage would be exclusively cortical.

The embryologic descriptions of Padget about the development of the venous system follow the scheme of five divisions of the brain (telencephalon, diencephalon, mesencephalon, metencephalon, myelencephalon). Subsequently, O’Rahilly and Müller [78], confirming previous observations, described 16 neuromeres in the brain (eight rhombomeres, three mesencephalic neuromeres, and five prosencephalic neuromeres) whereas recent work by Puelles and Rubenstein introduced significant aspects of segmental organization of the brain in relation with regional gene expression [79–82]. Further understanding of the segmental organization of the brain may help in clarifying several unclear aspects of the cerebral arterial and venous architecture. For instance, although a collector vein accompanying each nerve root has been described as the basic pattern of venous anatomy in the spinal cord [6, 83], it appears, in contrast to the radicular arteries, that the radicular veins may not follow segmental rules [32, 84]. For the brain, it remains therefore unclear whether a re-reading of the embryology of the venous system under the light of the above new considerations would modify the known descriptions. Similarly, it is unclear whether the adult organization of the bridging veins below the telencephalic level follows segmental rules and therefore if for each neuromere of the brain a segmental vein should be expected.

Emissary veins and dural arteriovenous shunts

Among the presented emissary veins, the jugular bulb and the emissaries of the hypoglossal canal have been described as the site of dural shunts [85–93]. The vein of the foramen cecum when present might be the actual site of some ethmoidal dural shunts since the shunt's site is often closely related to the presumed location of the foramen cecum.

The parietal, mastoid, and occipital emissary veins may theoretically be the original site of some dural shunts, which may appear as shunts of the SSS, sigmoid sinus, and occipital sinus or floor of the posterior fossa, respectively. The posterior condyloid vein similarly could be primarily involved in some of the dural shunts described as sigmoid-jugular bulb shunts or "foramen magnum" shunts. The emissary veins of the middle fossa through the foramen ovale, rotundum, lacerum, Arnold, and Vesalius, as well as the ophthalmic veins may also be the original site of some dural shunts described as lesions of the cavernous sinus.

The inferior petrosal sinus and the inferior petro-occipital emissaries may be primarily involved in shunts described as anterior condylar confluence shunts or even jugular bulb shunts. Remnants of the petrosquamous sinus and temporal (or postglenoid) emissary vein could be theoretically involved in lateral temporobasal shunts.

Whereas a shunt located on a BV is expected to involve directly the cortical veins for drainage, on the contrary, a shunt involving primarily an EV is expected to drain mostly to the sinus and not directly the cortical venous system. This becomes even more evident for sites adjacent to the aforementioned EVs as the anterior condylar confluence, which is located extracranially with no direct connection to any cortical vein. Thrombotic phenomena of the venous sinus itself or its connections with BVs and EVs (either as part of the pathogenesis or as consequence of the disease) apparently will modify this original tendency of the intact anatomic disposition. Could be that in certain stage of the disease, the EV with or without the adjacent part of the sinus, are thrombosed partially or completely, therefore are not detected in the angiogram. As a rule, the patency of the EVs in the angiographic description of a CDAVF is often neglected and their role in the venous draining pattern is not appreciated by the used classification schemes [94, 95]; to this contribute also their anatomic variability [63, 96].

Although no specific data on the histology and arterial supply of the wall of EVs were found in the literature, a shunt primarily involving the EVs should be expected to recruit additionally osseous arterial feeders [68, 85, 91]. In fact, the arterial feeders frequently recruited in shunts involving the above locations include mostly (starting from below) segmental branches of the vertebral artery, osseous branches of the occipital, ascending pharyngeal branches, transosseous branches of the posterior auricular, the stylomastoid and mastoid branch, artery of foramen rotundum, accessory meningeal, and other distal internal maxillary branches, ethmoidal branches of the ophthalmic artery, occasionally the superficial temporal artery, and rather secondarily more "purely meningeal" branches as the middle meningeal artery, posterior meningeal, or meningeal branches of the ICA. Therefore, a presumably EV-based CDAVF variety may actually include the so-called osteodural CDAVFs [32]. Considerations that involve EVs in the pathogenesis of any type of cranial dural shunts, including locations such as the tentorium, where no EV is present, seem to overemphasize their role [28].

Regarding the anterior cranial fossa, the anterior orbitofrontal BVs may join the SSS at its lowermost end, thus entering the dura at the floor of the anterior fossa just anterior to the crista galli [53]. Then, an anterior ethmoidal shunt draining into such a vein should be considered a BV-based shunt. On the other hand, except of the vein of the foramen cecum, which is considered a rarity for adults, there has been no description of another emissary vein connecting the SSS with the nasal venous system. In selective injections of nasal branches of the external carotid, intracranial venous drainage has occasionally been observed, as well as the opposite, superselective injections of fronto-orbital branches of the anterior cerebral artery showing venous drainage to the nasal venous system (our anecdotal data). The above support the concept of bidirectional venous drainage observed in emissary veins due to the lack of valves. Lasjaunias et al. considered the veins involved in ethmoidal dural shunts as emissary veins accompanying the olfactory nerve [68, 77], despite the fact that these veins do not fulfill the strict criteria of an EV, since no sinus is interposed. It seems that in the anterior cranial fossa, we are dealing with a peculiar venous disposition [97], resembling the spinal bridging-emissary vein configuration, where the BV pierces the dura and continues as EV without interposition of a sinus. In this context, phylogenetic implications (olfactory brain vs spinal cord venous anatomy) might be relevant, but beyond the frame of this paper.

The venous drainage of the shunts at the level of the lamina cribriformis is expected to be exclusive and direct cortical drainage, although an "epidural" nasal drainage has been also described [97]. Despite the fact that in the literature the venous drainage of all ethmoidal lesions appears seemingly identical (cortical), this underlying anatomic peculiarity may imply a diversification of clinical behavior among lesions grouped under the same name of ethmoidal or anterior cranial fossa dural shunts.

Conclusions

The distal segment of a BV embryologically, anatomically, and histologically seems to be part of the dural system.

Therefore, it can be not only secondarily involved in CDAVFs by carrying the shunted blood into the cortical venous system but also primarily by constituting the actual site of the arteriovenous shunt. In this case, the architecture and the clinical features of the shunt might be different in comparison with the classic sinus-based CDAVF. Although the above aspects are not as clear for the EVs as for the BVs, the EVs can also be the site of a CDAVF. One could assume that CDAVFs may develop in three distinct levels of the cranial venous system, from inside to outside: the bridging veins, the dural sinuses, and the emissary veins. The exact site of the original lesion may dictate the arterial feeders of the lesions, their venous drainage pattern, and as a consequence, their tendency for a certain clinical behavior. The area of the floor of the anterior cranial fossa is a peculiar location in terms of venous drainage anatomy. This peculiarity may be reflected in the nature, anatomical features, and clinical behavior of CDAVFs involving these veins.

Acknowledgments We wish to thank Professor V. Runge for his valuable comments on the manuscript and knowledgeable suggestions.

Conflict of interest We declare that we have no conflict of interest.

Financial support None.

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Comments

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It is common knowledge that the more sophisticated a classification, the better its predictive value, but the more complicated will be its applicability in everyday clinical care. The classification of dural AVF is a good example for this: The Toronto group proposed the most simplistic (and therefore easy to use) type of classification: "benign" dAVF have no cortical venous reflux, drain toward the heart, and have a good clinical prognosis, whereas "malignant" dAVF demonstrate cortical venous reflux and present with a high risk of hemorrhage and neurologic deficits [1, 2]. From the dichotomic classification, Borden moved on to further classify the malignant dAVF into those that had the reflux through a venous sinus and those that refluxed immedialtey into pial veins [3]. Given the large variability seen in patients with dAVF, it soon became obvious that more groups may even better subclassify these lesions and the Cognard classification had seven distinct subtypes [4].

While these classifications were mainly based upon analysis of the venous drainage assuming that all dAVF constitute the same type of disease, the Bicetre group challenged this assumption based on the finding that certain dAVF had a striking gender predilection [5, 6]. Their classification proposed that the primary role of the vein that is initially affected by the shunt will determine whether or not reflux will occur: If so, role of the affected vein was, to drain the brain, reflux will be present (and interestingly these dAVF had a significant male predilection) whereas those veins that are primarily involved into drainage of the bone will only present with cortical venous reflux if additional (secondary) outflow restrictions are present downstream from the shunt. While this classification helps to understand dAVF and their drainage pattern, it did not add to our treatment decision-making process.

The present classification represents an amalgamation of the different classification systems thus attempting to not only predict reflux but also to better predict clinical presentation and thus guiding our treatment decisions. It is based on the significant experience with and the deep understanding of dural arteriovenous fistulas of the senior author, Prof. Valavanis, who over the course of the past 19 years treated endovascularly the majority of the 211 patients with dAVF reported in this paper, and whose clinical and angiographical data were retrospectively reviewed and meticulously analyzed by the lead author, Dr. Baltsavias who treated several of the patients since 2009 and has to be commended for this major undertaking and for furthering our understanding of dAVF.

In the first part of the manuscript, Dr. Baltsavias introduces the concept of bridging and emissary veins and how they relate to the epidural spaces: While the bridging vein interconnect the pial veins with the dural sinuses, the emissary veins will interconnect the dural sinuses with the extracranial venous system thus being transitory conduits on opposite "borders" of the dural sinuses. The bridging veins represent pial-arachnoidal-dural connectors and are in their distal veno-sinusal junction related to the dural sinuses, i.e., they represent the lateral epidural spaces as proposed by the Bicetre classification. Given their location, shunts into these veins will invariably lead to cortical venous reflux.

The emissary veins on the other hand represent the connection of the dural sinuses to the extradural venous vessels and thus include the jugular bulbs, as well as the cavernous sinus. Shunts at these sites are expected to recuit osteodural feeder and are similar to the "ventral epidural spaces" of the Bicetre classification being primarily involved in drainage of the bone and leading primarily not to cortical venous reflux. The site of the shunt will thus not only dictate the venous drainage pattern but also the type of arterial feeder.

In the second part, the relation between the bridging veins and the leptomeningeal drainage is further evaluated highlighting the presence of thrombotic phenomena in the vast majority of cranial dAVF with purely leptomeningeal drainage. Dr. Baltsavias described three different patterns that can be encountered: a dural AVF engaging a bridging vein with occlusion of the veno-dural transition, a dural AVF into an isolated sinus, and a dural AVF into the veins close to the cribriforme plate.

Within the third part of this work, a revised classification of dAVF is proposed based on a detailed analysis of the angioarchitecture according to three factors: directness of venous drainage (depending on the location of the shunt), exclusiveness of the pial venous drainage (related to venous outflow obstruction), and venous strain (as evidenced by venous congestion or venous ectasias). These factors will lead to eight different subtypes of dural AVF and may be better suited to identify which patients present with aggressive clinical symptoms, which ultimately will benefit the patient by identifying patients at risk.

Finally, in the fourth part of this series, the thus developed classification scheme is tested in the series of the authors, and indeed, they were able to demonstrate that directness, exclusivity and signs for venous decompensation could better predict clinical outcome as compared to the simplistic classification of "benign" and "malignant" shunts.

This classification scheme will help to identify high-risk patients, and the authors have to be commended for their thorough and concise analysis of one of the largest series of dAVF managed at a single institution.

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The authors summarize the embryological aspect of the regional bridging and emissary veins based on a systematic review of the literature. They use the nomenclature in a strict way, paying special attention to the difference between bridging and emissary vein in terms of embryological aspect. This approach is quite unique and helps us to understand the functional anatomy of the venous drainage system of the brain and cranium.

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Dr. Baltsavias and the Zurich team are to be congratulated on this in-depth review of the intracranial venous vascular anatomy as it pertains to the relationships of the pial venous system draining toward the dural sinuses via the bridging venous system and the emissary veins representing the communication between the dural sinuses and the extracranial venous system except for at the anterior cranial fossa level where this may not occur due to the local absence of a dural sinus and the potential drainage via "bridging" leptomeningeal anastomoses connecting the adjacent pial venous system with the extracranial venous system at the level of the nasal fossa. This explains clearly the fact that patients with brain AVMs may present with nose bleeds and patients with cribriforme plate dural shunts may present with either epistaxis or intracranial hemorrhage.