Anatomy and physiopathology of the cerebral circulation

C. Paci
T. Carboni
R. Gobbato
S. Sanguigni
G. D'Andreamatteo
S. Sobrini
V. Urbano
A. Brandimarti
L. Curatola

Department of Neurology, "Madonna del Soccorso Hospital", San Benedetto del Tronto (AP), Italy
E-mail: cpaci@libero.it

Anatomy of the supra-aortic vessels

Blood is supplied to the human brain by two pairs of arteries: the internal carotid arteries (right and left) and the vertebral arteries (right and left).
The internal carotid artery (ICA) does not have collateral branches in its extracranial portion. It runs postero-laterally to the external carotid artery and its calibre ranges from 6.5-7.5 mm to 4.5-5.5 mm.
The ICA originates at the level of the fourth cervical vertebra or upper margin of the thyroid cartilage and ends in the cranium, in the parasellar region, below the anterior perforated substance. It can be divided into four segments: cervical, intrapetrosal, intracavernous, and supraclinoid.
The ICA can vary in its point of origin, course, caliber, and carotid siphon anatomy.
The vertebral artery (VA) originates from the postero-superior wall of the first portion of the subclavian artery; it reaches and enters the transverse foramen of the 6th cervical vertebra. It passes through the transverse foramina of the six cervical vertebrae, exits the transverse atlas, goes round the lateral mass of the atlas and perforates the atlo-occipital membrane and dura mater, entering the cranial cavity through the occipital foramen. The course of this artery can be divided into five segments: V0 (origin); V1 (pre-vertebral), V2 (cervical), V3 (atlantal), V4 (intracranial).

Anatomy of the intracranial circulation

The arteries of the brain originate from the two ICAs and from the basilar artery, which is formed by the union of the two vertebral arteries.
The intracranial circulation assumes the form of a polygon, called the polygon or circle of Willis.
The anterior cerebral artery (ACA): the ACA, from its point of origin, runs above the anterior clinoid process and continues between the optic chiasma and the olfactory trigone before deviating upwards, entering the interhemispheric scissure, where it tends to draw closer to the contralateral ACA with which it is connected via the anterior communicating artery (ACoA).
The middle cerebral artery (MCA) is divided into four parts: M1 (sphenoidal segment); M2 (insular segment); M3 (opercular segment); M4 (terminal segment).
The vertebral artery (VA): the VA is usually characterised by a regular course from its point of origin to its end, where it unites with the contralateral VA to form the basiliar artery. It can be divided into 5 segments: V0 (origin); V1 (up to its entry into the transverse foramen); V2 (from C1 to C2); V3 (from C2 until it enters the foramen magnum); V4 (from its entry into the foramen magnum to the origin of the basilar artery).
The basilar artery: originates from the union of the vertebral arteries; after a distance of about 3 cm it divides, at pre-pontine level, to form the two posterior cerebral arteries.
The posterior cerebral artery: the posterior cerebral artery is the anatomical and functional junction between the anterior circulation (carotid system) and the posterior circulation (vertebro-basilar system) of the polygon of Willis. It comprises a circular segment (which can be divided into the P1 or pre-communicating part

and the P2 or post-communicating part) and a cortical segment (which gives rise to the lateral and medial occipital arteries).

Cerebral venous circulation

The volume of the cerebral veins is greater than that of the cerebral arteries; the branches of the cerebral veins extend mainly over the free surface of the cerebral gyri; the cerebral veins have very thin walls (without muscle fibres), no valves, and abundant anastomoses.
The venous sinuses have rigid walls, are situated in the thickness of the dura mater, and have an endothelial lining. The venous sinuses receive blood from the cerebral veins and are direct or indirect branches of the internal jugular veins.
The cerebral venous circulation is made up of three systems:
1) superficial system: includes all the cerebral veins that, from the pial network, convey blood upwards (longitudinal sinus) or downwards (cavernous, petrosal or lateral sinuses)
2) deep system: receives blood from the basal ganglia, internal capsule, choroid plexuses and ventricular walls. Its supporting structure is the vein of Galen.
3) basal system (receives blood from the skull base and is comprised mainly of the Rosenthal vein).

Physiopathology of cerebral circulation

Metabolically, the brain is a highly active organ with limited energy resources of glucose and 0_2 (the brain's fuel). The brain (particularly in old age) can also use ketonic bodies. The arterial vascularisation is thus particularly important.
The cerebral circulation system can be defined as a multi-anastomotic terminal vessel network.
The brain receives around 750 cc of blood per minute, which corresponds to 50 cc/100 g, the heart receives 100 cc/100 g. The brain consumes around 50 cc of O_2/min, almost 15% of the total, and 80 mg/min of glucose. Autoregulation mechanisms keep the flow constant (within certain limits). Blood and brain tissue are separated by a morphological and biochemical barrier. Liposoluble substances (e.g. anaesthetics, drugs) are able to cross the blood-brain barrier best. This barrier can be temporarily altered by the circulation of substances in hyperosmotic concentrations or by acute hypertension. The brain does not contain precapillary sphincters which means that even flow rates (e.g. in the rat) increased by 80% are not associated with an increase in the number of perfused capillaries.
To safeguard the brain parenchyma as much as possible, autoregulation of flow takes place at the level of the cerebral microcirculation where control of intracranial vessel resistances ensures adequate cerebral perfusion even in highly precarious circulatory conditions. The physiopathological mechanisms underlying cerebrovascular autoregulation of arterial blood flow are:
1) the Bayliss effect
2) haemogasanalytic and chemoreceptor mechanisms
3) neurogenic mechanisms
1) the Bayliss effect is a myogenic response. It modulates arteriolar tone, increasing it when arterial blood pressure falls and reducing it when systolic pressure rises, and guarantees a stable and constant perfusion gradient even in the presence of large blood pressure variations (from 60 to 220 mmHg)
2) the haemogasanalytic mechanism acts on arteriolar tone, according to changes in O_2 and CO_2 concentrations (increases in PO_2 and reductions in PCO_2 levels increase arteriolar tone, hypoxia and hypercapnia reduce it). The chemoreceptor mechanism, whose receptors are located at pontobulbar level, modulates arteriolar tone according to tissue pH; indeed, increases in brain tissue acidosis induce reduction of arteriolar tone
3) In the neurogenic autoregulation mechanism, it is the neuron itself that modulates the blood flow velocity, modifying peripheral resistances through specific vasoactive peptides.

In normal conditions, the effects, on cerebral circulation, of activation or inhibition of the cervical sympathetic system are scarce or absent.
In the presence of hypercapnia there is increased blood flow in all brain regions, associated with a reduction in glucose consumption. Even the large arteries contribute, by dilating, to the increased flow. The dilatory effect of hypercapnia seems to be mediated by increased the increase of $[H_+]$ in the extracellular cerebral fluid. The vasodilatory response to the hypoxic stimulus appears when the PO_2 drops below 50 mmHg; in the presence of hyperoxygenation there are no substantial variations in cerebral blood flow. If the metabolic activity increases, consumption of O_2 and glucose increases, leading to production of CO_2.

The ABC of transcranial colour-coded Doppler

V. Inchingolo[a]
M.A. Pacilli[b]

Departments of Neurology[a] and Cardiology[b]
IRCCS "Casa Sollievo della Sofferenza" Hospital, San Giovanni Rotondo (FG), Italy

Transcranial colour-coded Doppler (TCCD) is a non-invasive technique for studying brain circulation and parenchyma. It provides both morphological and haemodynamic information about cerebral arteries and veins. As for the ultrasound study of other vascular districts, TCCD exploits the coupling of B-mode with colour-Doppler-mode or power-Doppler-mode for the study of cerebral vessels. The technique uses sector probes with frequencies of between 2 and 3 MHz. These probes are equipped with an ultrasound beam that is roughly triangular in shape: narrower at the surface so as to be able to penetrate a very limited area of cranial theca, and wider in depth so as to be able to display the widest possible area inside the skull. The examination is performed through the same windows used for transcranial Doppler (TCD): temporal, occipital, orbital and sub-mandibular. In some cases a frontal window can also be used.
TCCD requires a detailed knowledge of topographic intracranial anatomy because it is necessary to study B-mode scanning planes in order to locate the arteries of the cranial base and recognise any abnormalities in their course. With TCCD, it is possible to correct the insonation angle to obtain faithful estimates of flow velocity, avoiding errors in tortuous arterial segments. The Doppler signal can be detected along the entire course of each artery, greatly increasing the accuracy of diagnosis, particularly in cases of arterial stenosis. Second-generation echo contrast media make it possible to study the arterial circulation even in patients with poor ultrasonic windows, reducing to 2-4% the proportion of non-assessable cases.

B-mode study

The exploration of the cranial base in the B-mode, according to axial planes through brainstem, is usually the first examination step. Highly detailed ultrasound images can be obtained using the fundamental harmonic or the second harmonic.
The **temporal window** corresponds to an area located above the zygomatic process of the temporal bone, anterior to the attachment of the upper ear, where the cranial theca is thinner. The depth of exploration should initially be adjusted to about 14 cm, to cover everything in the skull and get an overall picture. Later, the depth of exploration can be adjusted on the basis of the established structures of interest.
Through the temporal window in an axial cantho-meatal scan you can identify anatomical structures, which serve as landmarks for recognising cerebral arteries. The main ones are the following: the edge of the lesser wing of sphenoid bone, which laterally demarcates the middle from the anterior cranial fossa, the brainstem which, in the middle, appears as a slightly hypoechogenic butterfly-shaped image, and the contralateral skull cap that appears, at a depth of about 14 cm, as an upward concave hyperechogenic thick line. Still in the axial plane, tilting the probe upwards about 10°, it is possible to explore the diencephalic plane and see other anatomical structures: the third ventricle appears as two parallel hyperechogenic lines running in a forward-to-backward direction. Because of its location the third ventricle is important in assessing the midline shift in parenchymal studies. The pineal gland appears as a hyperechogenic area located behind the third ventricle. The two thalami are two symmetrical, weakly hypoechogenic areas located on both sides of the third ventricle. With an upwards shift of about 30° from the axial plane, it is possible to explore the sovra-diencephalic plane, where the cella media of lateral ventricles (two parallel hypoechogenic structures extending in a backward-to-forward direction) can be displayed, as well as, by means of appropriate partial rotation movements of the probe on its main axis, the frontal and temporal horns of the lateral ventricles. In this plane, the surrounding isoechogenic areas correspond to the white matter of the frontal, parietal and occipital lobes.
The three planes through the temporal window (mesencephalic, diencephalic and sovra-diencephalic), are used respectively for the exploration of the circle of Willis, for densitometry (study of the microcirculation by

means of contrast media), and for the study of diseases of the brain parenchyma (e.g. expansive processes, vascular malformations).
Another exploration plane in B-mode from the temporal window is obtained by rotating the probe 90 degrees on its axis in an anticlockwise direction. This coronal plane allows the visualisation of other anatomical landmarks useful for subsequent identification of the intracranial vessels. These landmarks are: the upper edge of the petrous bone (hyperechogenic line that leads lateral-medially in a backward-to-forward direction) and, within it, the carotid canal that appears hypoechogenic and bound by hyperechogenic walls. Also in this plane, further forwards, the frontal horns of the lateral ventricles can be displayed. In this plane the hyperechogenic falx extends the midline cranially to the skull cap.
The **occipital window** corresponds to a wide area in the nape region, below the occipital bone. It is possible to use a median and lateral approach. Through this window, in B-mode, you can display, following an axial plane directed towards the nasion, a roundish hypoechogenic area corresponding to the foramen magnum. With a slight shift of the probe caudally, the atlas can be displayed. The occipital window is used to study the vertebro-basilar circle.
The **orbital window** corresponds to the orbital foramen on both sides. After an appropriate reduction in the ultrasound emission power to prevent potential retinal damage, the probe is placed on the eyeball, with the eyelid closed. This window can be used to study the ophthalmic artery, an important collateral, in cases of carotid occlusion. The landmark at this level is the eyeball.
The **sub-mandibular window** corresponds to an area located medially to the corner of the jaw. In this region, with the probe oriented cranially, you can study the internal carotid artery (ICA)Iin its extracranial distal tract, before it enters the skull.
A **frontal window** has been described. It can be used in certain circumstances to study arterio-venous malformations or aneurysms of the anterior cranial fossa.

Colour Doppler study of intracranial arteries

As mentioned, through the temporal window, it is possible to study the arteries of the circle of Willis with colour or power box, and subsequently detect the Doppler signal. If the probe is correctly positioned according to an axial mesencephalic plane in a B-mode exploration, the colour box overlap will allow immediate identification of the main part of the circle of Willis (Fig. 1). Since the arrangement of the arteries in the mesencephalic plane is not perfectly flat, little movements of the probe, downwards and upwards, and even small rotations on the main axis of the probe, can be used to reconstruct the three-dimensionality of the circle. In this way, it becomes possible to distinguish three mesencephalic planes: lower, middle and upper. Starting from the lower mesencephalic plane, the terminal portion of the ICA (C2-C1 segment) is displayed medially to the wing of the sphenoid bone. By up-tilting the probe a few degrees, it is possible to identify the posterior cerebral artery (PCA), which, with its P1-segment (pre-communicating), where the flow is towards the probe (red), and its P2-segment (post-communicating), where there is a first tract towards the probe and a second tract away from the probe (blue), surrounds the mesencephalon.
In the middle of scan it is possible to see a rounded arterial segment with a bi-directional signal flow, which corresponds to the top of the basilar artery (BA) in a transverse plane. Laterally, a few degrees upwards,

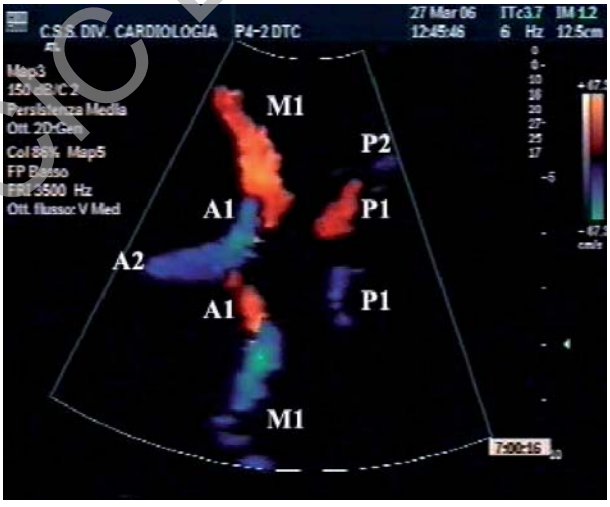

Fig. 1 - Circe of Willis. Colour-mode, axial mesencephalic plane through the temporal window. See the text for abbreviations.

you can find the main trunk of middle cerebral artery (M1 segment of the MCA), with flow towards the probe, which runs behind the edge of the lesser wing of the sphenoid bone. More medially, you can display the A1 segment of the anterior cerebral artery (ACA), with flow away from the probe. This segment runs approximately horizontally towards the midline, where it joins with the contralateral through the anterior communicating artery (ACoA). This is a very short vessel visible only in a small percentage of cases. However, its functionality can be tested with appropriate manoeuvres of compression of the proximal common carotid artery. After joining with the contralateral through the ACoA both these A2 segments of the two ACAs run closed first horizontally and then arching cranially, in the medial longitudinal fissure of brain, following the knee of the corpus callosum. Afterwards, each artery divides into its branches (A3 segments). In front of the mesencephalon, it is possible to display, albeit not consistently, the posterior communicating artery (PCoA), which runs from the ICA to the ipsilateral PCA. Its flow direction is usually towards the posterior circulation, but can vary depending on the haemodynamic state. When the PCoA is not displayed directly, you can test its functionality using compression tests.

Tilting the probe a few more degrees, the curves of the M1 segment of the MCA can be followed: typically, in the axial plane, there is a first curve showing anterior concavity and, a second one, with posterior concavity. In the coronal plane, instead, immediately after its origin, the MCA describes an upwards, slightly concave curve. It then divides into the M2 and M3 segments running in the Sylvian scissure. These vessels are detected by appropriate movements of the probe in multiple planes to follow their upwards, frontal and backwards course (candelabrum-like arteries). Usually, an overview of the main part of the circle of Willis can be gained by rotating the probe a few degrees on its axis in an anticlockwise direction (semi-coronal plane), because the plane of the cranial fossa, on which the circle of Willis lies, is not horizontal but slightly raised and forward positioned.

With last generation equipment, lenticular striate arteries are sometimes displayed approximately 1 cm after the MCA origin. These little arteries are very important since they supply part of the basal nuclei and internal capsule.

The coronal scan plane makes it possible to display all the ICA segments. The ICA is characterised by an initial tract with flow away from the probe (at the base of the skull and in the first stretch in the canal of the petrous bone, C5 segment), after which, changing direction, it shows flow towards the probe (in the second stretch of the canal until its escape through the foramen lacerum, C4 segment). Within the cavernous sinus, the ICA describes a double curve: the "siphon" (C2-C3 segment), initially with flow away from the probe, then with flow towards the probe. Finally, in its last segment (C1), with flow towards the probe, the ICA runs almost vertically upwards and divides into its terminal branches: the anterior chorioidea artery (AChoA), the PCoA, the MCA and the ACA. Together with these two last arteries the terminal ICA forms a T division, frequent site of stenosis and occlusion. The other two smaller terminal branches, the AChoA and the PCoA, can be displayed, although not consistently, with a scan in the axial plane. The first, horizontal, runs dorsally, just laterally to the P2 segment of the PCoA; the second, as already mentioned, runs dorsally to join with the ipsilateral PCA. Still in a coronal scan, but in a slightly dorsal plane, the last segment of BA is displayed, with the flow usually towards the probe, and the antero-superior cerebellar artery, originating from the BA just before the top.

Through the occipital window, with the colour box, vertebral arteries (VA) in the V3 segment are displayed surrounding the sides of the atlas (atlas loop). Vertebral arteries in V3 have a first segment running towards and a second one away from the probe. Thereafter, the V4 intracranial segment running away from the probe converges with the contralateral to form, at a depth of 70-80 mm, the BA, also with flow away from the probe (Fig. 2). In an axial plane small movements of the probe are required, both from a median and

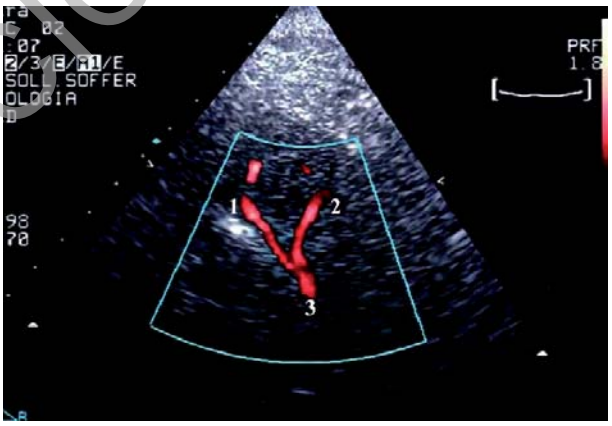

Fig. 2 - The vertebral arteries in the V4 segment (1 and 2) and the basilar artery (3). Power-mode, axial plane through the occipital window.

from a lateral approach, to display the vertebro-basilar system, due to its frequent tortuosity. With these movements the postero-inferior cerebellar arteries are also displayed arising from the respective V4 segment of the VA, and the anterior-inferior cerebellar arteries arising from the proximal segment of the BA.
TCCD examination through the temporal window is usually performed behind the headboard of the bed, with the patient in the supine position. Study of the posterior circulation through the occipital window can be performed with the patient seated and the operator back positioned, but in patients unable to remain seated (as is often the case in acute stroke), it becomes necessary to adopt the same position described for the temporal window, with the head left or right rotated, or simply with the patient in a lateral decubitus position.

Anatomical variations of the circle of Willis

The following are the main anatomical variations of the cerebral circulation found with TCCD: 1) direct origin of the PCA of one or both sides from the ipsilateral ICA, with subsequent hypo-aplasia of the P1 segment (15% of the population); 2) hypo-aplasia of the A1 segment of the ACA (in this case the A2 segment originates from the contralateral A1); 3) hypoplasia of one of the two VA (most often the right); 4) hypo-aplasia of one or both PCoA.

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