Extracranial and Intracranial Sonographic Findings in Vertebral Artery Diseases

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Objective. The aim of this review is to illustrate the sonographic features that can be detected in vertebral artery (VA) diseases. Methods. We conducted a review of sonographic findings in VA diseases. Results. Various VA diseases are described, and sonographic techniques and features are discussed. Conclusions. Posterior circulation vascular imaging can be performed by means of various neuroimaging techniques. Intra-arterial angiography remains the reference standard. The use of this technique has become even more widespread since it has become possible to perform endovascular procedures; it is, however, an invasive procedure that is associated with a not irrelevant level of risk. Computed tomographic angiography and magnetic resonance angiography with and without contrast agents have been proposed as less invasive alternatives, although these techniques can only be performed in the radiology unit and may not be readily available in daily clinical management. Sonography, which combines an extracranial and intracranial evaluation, is highly suited to the assessment of the vertebrobasilar system on account of its widespread availability and its unique capacity to study real-time hemodynamics. Furthermore, new sonographic applications and sonographic contrast agents have improved the sensitivity and specificity of this technique with regard to diagnostic accuracy for the posterior circulation. Key words: posterior circulation diseases; sonography; transcranial Doppler sonography; vertebral arteries.
such patients. Experienced vascular surgeons can even directly reconstruct VA stenosis. Endovascular procedures such as angioplasty and stenting, sometimes in conjunction with intra-arterial thrombolysis, have proved feasible, yielding promising results, although with higher complication risks than in the carotid territory.11–14 The existence of specific surgical strategies for VA disease has conferred greater importance on accurate vascular imaging of the posterior circulation. Until very recently, detection of a posterior circulation stenosis did not indeed alter clinical management of this condition, there being no specific treatment available other than medical therapy: antithrombotic or anticoagulation.

**Cerebrovascular Imaging**

The 4 methods available to date for VB vascular imaging are extracranial and intracranial sonography, computed tomographic angiography (CTA), magnetic resonance angiography with (CE-MRA) and without contrast agents, and conventional catheter intra-arterial angiography (IAA). Each of these techniques has its advantages and disadvantages.

Intra-arterial angiography remains the reference standard for the identification of VA stenosis; it is, however, an invasive technique that is accompanied by a risk of procedural iatrogenic stroke in up to 2% of cases15 and does not offer the possibility of obtaining structural images of the brain simultaneously with the vascular images. Moreover, there may be specific technical procedural difficulties such as selectively finding and injecting the contrast agent into the origin of the vessel, with reduced sensitivity if the injection is performed in the subclavian artery (SA).

Magnetic resonance angiography with and without contrast agents, also with new arterial spin labeling techniques to detect vascular integrity, and CTA have been proposed as powerful alternatives, with higher sensitivity and specificity for CE-MRA, lower for CTA, with respect to sonography, even when compared with IAA.16–18 Computed tomographic angiography can be performed extremely rapidly, although despite being less invasive than IAA, it is associated with a potentially toxic load from contrast agents and ionizing radiation. Although CE-MRA partially avoids the toxicity- and radiation-related problems, this technique may be less widely available and is more time-consuming than CTA. All of these conventional radiologic techniques, which are becoming more and more diffuse even in nonspecialized centers, are expensive and require patients to be delivered to a radiology unit. However, their main limitation is that imaging is based on the flow within the vessels, which means that definition may be scarce in cases in which flow is turbulent or severely reduced, also making interpretations of radiologic imaging highly operator dependent.

Sonography has been extensively used in the evaluation of the VB system, owing to its low costs, widespread availability, noninvasiveness, and the possibility of being performed at the bedside.19–21 Its main disadvantages, which are common to all sonographic examinations, are that it is operator dependent and that its sensitivity is reported to be lower than that of either CTA or MRA. However, it should be borne in mind that sonography offers opportunities that cannot be explored by means of other imaging techniques, ie, its unique capability to investigate real-time hemodynamics, which is impossible with conventional neuroimaging, for both intracranial and extracranial segments in the same session. Moreover, new advances for examining the whole intracranial segment “at a glance” have been made even with only transcranial Doppler (TCD), with new software that transforms the signals from different depths into a tracing similar to the cardiac M-mode with color intensity indicating the direction and velocity of the flow: the “power motion mode.”22,23 The use of sonographic contrast agents for transcranial color-coded duplex (TCCD) imaging have further enhanced intracranial VA tract imaging,24–28 thereby increasing its diagnostic sensitivity.

The aim of this review is to describe the sonographic features that can be detected in VA diseases.

**Anatomy of the VA**

The VA is divided into 4 segments.29 V0 is the origin. The V1 tract extends from the SA, anterior to the C7 transverse process, to the entry point of the C6
foramen transversarium. The V2 tract lies within the C6–C1 intertransverse foramina. The V3 segment, at the Tillaux point, extends in a loop from the arch of the atlas to the foramen magnum. The V4 intracranial segment extends intradurally, gives rise to the posteroinferior cerebellar artery (PICA), and extends from the foramen magnum to the contralateral VA to form the basilar artery. The artery is most vulnerable anteriorly at C7, laterally from C3 to C7, and posteriorly at C1 and C2.

**Sonographic Technique**

The extracranial V1–V3 segments can be approached anteriorly on the neck (V1–V2) and from the lateral posterior suboccipital region (V3), with longitudinal and transversal projections. The left V0 origin is more difficult to visualize than the right V0 because it arises from deeper in the chest. Lower-frequency linear transducers, with a higher penetration capacity, yield better results, whereas velocity measurements with continuous Doppler imaging have become less used in clinical practice because of its limitation of being a “blind” technique.

The intracranial V4 segments can be insonated through the suboccipital transforaminal window by TCD imaging with a 2-MHz pulsed wave probe and by TCCD imaging with a 2.0- to 3.5-MHz sector array transducer, with regard to the ultrasound apparatus. The left and right VAs are more easily identified with TCCD imaging. With an adequate subnuchal acoustic window, the origin of the PICAs in the distal V4 tract can also be insonated, resulting in flow directed in the opposite position with respect to the VAs. In a case of an inadequate transforaminal window or when the neck conformation and forward bending are particularly difficult, sonographic contrast agents can be used to improve detection of the V4 segments, the PICAs, and the proximal tract of the basilar artery. Contrast agents thus markedly increase the sensitivity and diagnostic accuracy, particularly in the detection of acute basilar artery occlusion and in follow-up for basilar stenting. However, under the best conditions, through the suboccipital window, sonography allows visualization of two-thirds of the basilar artery, even with the aid of contrast agents. The basilar artery tip can be examined by means of a transtemporal approach, and the median/distal part of the vessel may sometimes then be identified with some difficulty by TCCD imaging.

**Pathologic Findings**

Pathologic findings of the VA that can be detected by sonography include (1) caliber variations and hypoplasia, (2) course anomalies and cervical compression, (3) proximal and distal occlusion, (4) proximal stenosis with and without cervical compensation, (5) V4 intracranial stenosis, (6) dissection, and (7) subclavian steal.

The most frequent locations of VA atherosclerotic damage are at the sites of vessel bifurcation, namely at the V0/V1 origin and in the distal V4 tracts, ie, the VB junction. Arterial dissection may be located more frequently in the V2 and V3 segments (35% and 34%), the V1 segment (20%), and the V4 segment (11%).

**Asymmetries, Hypoplasia, and Abnormal PICA Termination**

Congenital variations in the posterior circulation are commonly observed in routine clinical diagnosis but are of no clinical relevance in most cases. Several diagnostic techniques have detected caliber asymmetry, with most observations revealing a larger left- than right-side VA diameter. In an early pathoanatomic study, hypoplasia was defined as a lumen diameter of less than 2 mm, this definition being supported by a sonographic study that revealed a decrease in blood flow velocity in VAs with diameters of less than 2 mm. Nonetheless, other authors have proposed a diagnosis of hypoplasia when the caliber is less than 3 mm and when the Doppler spectrum shows a high resistive pattern. When the caliber is congenitally smaller...
than 3 mm, resistive indices increase as the blood flow through the artery is reduced; this is considered a hypoplastic vessel with reduced wall distensibility.3 The diameter of the contralateral normal vessel is usually larger. Furthermore, a hypoplastic VA is frequently associated with an abnormal termination in the homolateral PICA; in these cases, post-PICA occlusion and an abnormal PICA termination cannot easily be differentiated exclusively with cervical sonography and with no evident clinical symptoms (Figure 1B).48–50 When the diameter of the hypoplastic vessel is very small (ie, <2.0 mm), a further increase in the resistive indices may be observed (Figure 1C). In such cases, an extracranial investigation alone is unlikely to reveal pre-PICA occlusion, although with more reduced diagnostic velocities in the latter case,49,50 TCD or TCCD being required to provide further diagnostic information; a similarly high resistive pattern in the intracranial V4 segment confirms the patency of the distal vessel and thus indicates vessel hypoplasia. In such cases, the presence of a clinical history may be important to make a differential diagnosis between acute symptomatic distal occlusion of an eventual dysplastic/ hypoplastic vessel and congenital asymptomatic non–clinically relevant hypoplasia, a second test being confirmative.

Tortuous VA Course and Cervical Intertransverse Segment Compression

Vertebral artery course anomalies due to congenital variations related to their embryogenesis are frequent.51 Indeed, length anomalies, tortuosity, and kinking of the V2 segment are commonly observed in routine clinical practice, although without any related clinical symptoms (Figure 2, A–C). Cases in which a VA intervertebral loop causes radicular compression and widens the intertransverse foramen, consequently requiring decompressive surgery, are rare.52 Cervical spine arthrosis may, like rheumatoid arthritis, cause vertebral atlantoaxial and subaxial subluxation with spinal cord compression, VA loop formation, and vascular compression.53 A tortuous course of the intertransverse V2 segment of the VA may be observed in such cases, accompanied by an increase in the resistive indices and changes in blood flow velocities (Figure 2, D and E).

Because the VAs can cause catastrophic iatrogenic complications during cervical spine surgery and manipulation,30 all of these abnormalities should be borne in mind by surgeons when they approach the cervical and craniospinal regions. Moreover, with the advent of intravascular treatment for distal intracranial VA
and basilar artery stenosis, the interventional radiologist should also be aware of any vessel course anomalies that may impede, for example, the passage of an intravascular catheter and cause local traumatic dissections when repeated unsuccessful selective VA catheterizations are attempted.

**Proximal and Distal VA Occlusion**

Hemodynamic changes can be indirectly detected in the V2 segment in cases of both proximal and distal VA stenosis/occlusion.48–50

In cases of proximal occlusion, the flow may be absent in the V2 segment, thus indicating extension of the atherosclerotic process from the origin to the whole cervical segment (Figure 3A).

However, if the V2 segment is patent, flow often can be detected through visible collateral cervical branches arising from the external carotid artery and refilling the intertransverse segment.

In distal intracranial V4 occlusion, the V2 segment may be patent. If evaluation of the VA is limited to the extracranial segment, the criteria on which diagnosis of the distal V4 segment occlusion is based are only indirect: they consist of the observation of a normal vessel caliber in the intertransverse segment but with altered resistive indices and interrupted diastolic flow (Figure 3B).49,50

However, the site of intracranial V4 occlusion, ie, before or after the origin of the PICA, is important to identify, as V4 occlusions distal to the ori-
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gin of the PICA may be overlooked with only cervical examination because no prominent change of flow velocity and/or the flow signal is expected in the intertransverse segment in this case. Some authors have suggested that differences in the VA caliber, velocity measurements, and aspect of Doppler spectra may be used as criteria for differentiating intracranial VA occlusion from hypoplasia and an abnormal termination, although agreement on the usefulness of such measurements is not unanimous.

Nonetheless, for the differential diagnosis, the altered resistive indices in the V2 segment observed in cases of severe vertebral hypoplasia or in an abnormal V4 segment that terminates into the PICA may be misinterpreted as V4 occlusion. Direct evaluation of the V4 segment by means of TCD and TCCD imaging yields important information on distal vessel patency and hemodynamics that may support and confirm the diagnosis in these cases. Indeed, a hemodynamic sonographic evaluation is fundamental because MRA and CTA may, in low-flow conditions, not visualize the vessel.

**Proximal VA Stenosis With and Without Cervical Compensation**

When the proximal V0–V1 segments present hemodynamic stenosis but the intertransverse segment is patent, compensatory flow may arise from the cervical branches, refilling the V2 segment. In such cases, the resistive and pulsatility indices are reduced in V2, whereas minimal alterations are observed in V3 and V4 if compensation is sufficient (Figure 4, A–C). Evaluation of the complete vertebral axis is thus mandatory because proximal stenosis may escape diagnosis if only intracranial CTA or MRA, which would in such cases show a normal distal V4 segment, is performed.

By contrast, a “steal” phenomenon, ie, retrograde flow during systole and orthograde flow during diastole, may be observed in V4 in severe proximal V0–V1 steno-occlusive disease when compensation via cervical vessels is insufficient. This finding has not yet been described in the literature and refers to our experience in consecutive performing TCD or TCCD imaging to assess intracranial vessel patency in cases of VA proximal diseases. It is reasonable to consider that,
when the V4 segment distal to the occlusion is patent, the steal phenomenon is directed toward the PICA (Figure 4, D–F). This mechanism supports blood flow to the cerebellum and clearly indicates that the distal segment is patent and not involved in the atherosclerotic process. Conventional neuroimaging may lead to false interpretations because the biphasic low flow in the V4 segment may reduce visualization and consequently be interpreted as occlusion.

**V4 Intracranial Stenosis**

Stenosis of the V4 segment and the basilar artery can be detected with either TCD or TCCD imaging. When using TCD imaging, the V4 segment corresponds to an insonation depth of 65 to 80 mm, whereas the basilar artery can be insonated at higher depths. The advent of the power motion mode can help identify the whole V4 segment at a glance even with TCD imaging, especially in cases of occlusive disease (Figure 5A). Transcranial color-coded duplex imaging may first help differentiate the left from the right V4 segment and then to locate the site of the stenosis within the vessel by searching for an aliasing effect or a color defect, which indicates a high or low velocity, respectively (Figure 5B). Depending on the extent of the stenosis, both increased and decreased flow velocities, accompanied by Doppler spectrum broadening and altered resistive indices, may be observed, with normal systolic and diastolic values ranging from less than 140/100 cm/s for the basilar artery and less than 120/90 cm/s for the VA.

Nonetheless, because a TCCD image of the vessel is derived from the inward flow, vascular images must always be associated with a Doppler hemodynamic evaluation because nonhemodynamic stenosis cannot be detected. In contrast, congenital tortuosity can easily be visualized, thus allowing it to be differentiated from a flow velocity modification related to a course variation.

**Vertebral Artery Dissection**

With the progress of high-resolution sonography, it is possible to noninvasively diagnose a dissection of the extracranial VA when it is located in the proximal V1 segment, ie, at the entrance of the artery in the transverse foramen at C6 or at the V0–V1 origin. Cervical sonographic findings in the acute phase may vary from vessel occlusion to the observation of surface irregularities and intramural hematoma, especially in V1. Occasionally, 3 lumina with a mobile intimal flap may be observed, although this requires high-resolution echographic systems and a skilled sonographer. A follow-up examination may confirm the diagnosis when good recanalization is observed because atherosclerotic lesions rarely disappear.

Dissections located in the V3 and V4 segments cannot be visualized directly on the screen; the
diagnosis in such cases is based on indirect signs in the course of the cervical intertransverse artery, such as a high-resistance flow pattern, indicating distally obstructed flow with a normal caliber. Transcranial duplex imaging, with the use of contrast agents if necessary, may confirm or support the diagnosis when the distal V4 segment is occluded and cannot be visualized. Even in this case, clinical symptoms are fundamental for correct interpretation of the findings.

Subclavian Steal Effect
A subclavian steal effect can arise from an obstruction of the brachiocephalic trunk or when there is SA stenosis or occlusion in the proximal segment before the VA origin. If the caliber of the VA is normal, the blood supply to the arm is maintained through a steal effect from the contralateral side, via a vertebrovertebral crossover from the intracranial V4 segments that unite to form the basilar artery. In approximately 25% of cases, a carotidobasilar supply with retrograde flow in the basilar artery or a steal effect via the branches of the external carotid artery may be observed.

Steal effects vary according to the severity and extent of the SA stenosis or occlusion, as reported by authors who have investigated this effect even by means of the cuff upper arm compression test, which induces reactive arm hyperemia and consequently the steal effect. Summarizing, steal effects are divided into 3 grades depending on the severity of the hemodynamic effects:

Initial Subclavian Steal Effect
If the SA stenosis is in the early stages and not yet severe, the only signs may be a reduction in the systolic blood flow velocity in the homolateral V2 segment with a slight alteration in the resistive indices. In such cases, blood steal and to-arm flow are examined only during arm muscle exercise; hyperemia induced by the cuff compression test inverts the flow direction in the VA and is associated with the appearance of to-arm flow on the release of compression (Figure 6A).

Incomplete Subclavian Steal Effect
When the SA stenosis is moderate, to-arm blood may be carried partially through the stenotic SA and partially through a contralateral steal phenomenon. In such cases, under basal conditions, the homolateral VA shows biphasic alternating flow, which is in the to-arm direction during systole and the to-brain direction during diastole. The cuff compression test increases the to-brain flow during compression and the to-arm flow on the release of compression (Figure 6B).

Complete and Manifest Subclavian Steal Effect
In cases of high-grade proximal SA stenosis or occlusion, the blood supply to the arm is maintained exclusively by the contralateral VA, in which blood flow velocity increases, and by inversion of the flow direction in the homolateral VA. The hyperemia cuff compression test does not usually induce substantial hemodynamic changes, except for a slight to-arm flow increase on the release of compression (Figure 6C).

The subclavian steal effect should always be taken into account when an alteration in the V2 segment resistive indices is observed. The possibility sonography offers of detecting functional hemodynamic changes in response to hyperemic arm compression tests may help identify conditions that are still in their early stages and may otherwise escape detection.

Final Considerations
Vascular imaging of posterior circulation may be performed by means of several neuroimaging techniques. Intra-arterial angiography is still considered the reference standard, although this technique is invasive and carries procedure-related risks. Computed tomographic angiography and MRA with and without contrast agents are not only highly sensitive for the posterior circulation but are also less invasive than IAA; they cannot, however, be used for vascular screening purposes because CTA is potentially toxic on account of the contrast agents and radiation involved, whereas MRA is expensive and not always available. Interpretation of images may also be operator dependant. Sonography, which combines cervical imaging with TCD or TCCD imaging, contrast agents, and functional tests, is noninvasive and widely available and sheds light on the pathophysiologic characteristics. However, its sensitivity is reported to be lower than that of either CTA or CE-MRA.
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Figure 6. Cervical color Doppler images of different grades of subclavian steal. A, Initial subclavian steal. Note the reduced systolic velocity and altered resistive indices in V2. A1, Cuff compression induces the appearance of retrograde flow on the release of compression (arrow). B, Incomplete steal. In the basal condition, flow alternates in V2. B1, Cuff compression increases the retrograde flow on the release of compression (arrow). C, Complete steal. In the basal condition, flow is totally anterograde with increased flow velocities on the normal side (left) and retrograde on the subclavian stenosis side (right). C1, Cuff compression increases the retrograde flow on the release of compression (arrow).
because it requires skilled neurosonologists, is operator dependent, and provides a limited view of the VAs. In specific cases, data collected from more than one imaging technique may increase the diagnostic accuracy of posterior circulation evaluation. In this regard, the advantage of sonography is that it offers the possibility of coupling vascular imaging with real-time data on functional hemodynamics.

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