Noninvasive Angiography for the Diagnosis of Vertebral Artery Disease Using Doppler Ultrasound (Vertebral Artery Doppler)

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SUMMARY A transoral noninvasive procedure in the oropharynx using local anesthesia was applied to detect flow in the vertebral arteries with a bidirectional continuous-wave Doppler ultrasound system. Common carotid artery compression was used to identify the vertebral artery. Flow direction, amplitude of flow signals, diastolic flow, and reaction of flow on common carotid artery compression served as diagnostic parameters. The procedure was applied in 90 patients of whom 42 underwent angiography. The method has proved to be 82% accurate. It was most reliable in the diagnosis of occlusion or aplasia, subclavian steal and normalcy, and was less reliable in the detection of stenosis or hypoplasia of a vertebral artery. Eleven patients with subclavian steal, five patients with a missing vertebral artery, three patients with hypoplasia or stenosis, and 15 patients with normal angiographical findings were correctly diagnosed by Doppler; normal Doppler findings were present in three patients with a missing or stenosed vertebral artery. Those patients (five) with Doppler indications of subclavian steal (one patient), missing vertebral artery (two patients), or stenosis (two patients) had normal angiograms. Application of the Doppler procedure, after 11 subclavian endarterectomies, informed the surgeon immediately about the hemodynamic effect of surgical intervention. Rethrombosis was diagnosed in two patients by postoperative Doppler examination.

Introduction

THE DIAGNOSIS of disturbed vertebral artery perfusion by palpation and auscultation is insufficient because of high fallibility. Noninvasive methods such as ultrasound pulse echo registration, rheographic exploration, electronic sector scanning, or percutaneous Doppler measurements in the region of the mastoid have not yet proved to be of clinical relevance.1,4 Either the reliability of these methods is poor or the requirements of time and equipment are too high to be used as screening procedures. The diagnosis of vertebrobasilar disease with screening methods is further complicated by frequent anatomical variations in the vertebrobasilar system.9,12

The nearest approach to the vertebral artery with appropriate knowledge of topographic anatomy is through the mouth. In this paper we describe a procedure in which the bidirectional continuous-wave Doppler ultrasound system described in a previous paper is used.14 The ultrasound probe of the Parks 806 Doppler device (Parks Electronic Laboratory, Beaverlton, Oregon) was placed manually on the mucous membrane of the oropharynx between two transverse processes. Gag reflexes were controlled by local anesthesia previously sprayed into the pharynx. Flow toward or away from the skull can be diagnosed, the amount of flow in each vertebral artery can be roughly quantitated, and the peripheral resistance can be approximately evaluated. Additionally, common carotid artery compression revealed the function of the posterior part of the circle of Willis. Doppler examinations in patients with subclavian steal14 before and after endarterectomy in the proximal subclavian artery showed the hemodynamic effect of the operative intervention on cerebral circulation and helped to diagnose rethrombosis.

Anatomy and Hemodynamics

The vertebral artery normally rises as the first branch of the homolateral subclavian artery and traverses the transverse foramina of the cervical spine.11,12,16 The vessel lies 0.5 to 2 cm deep to the surface of the oropharynx, with parts of the prevertebral and scalene muscles and the dorsal mucous membrane of the pharynx interposed. Normal variations in the extracranial vertebral system are more frequent than those in the carotid arteries. Both autopsy findings and angiograms often reveal differences in caliber between the left and right vertebral arteries, and hypoplasia or aplasia of one vertebral artery is not infrequently observed in asymptomatic patients.8,11

In the normal physiological situation, blood in the vertebral artery flows toward the skull throughout a cardiac cycle.9,7 Reverse flow direction may be present in patients with severe stenosis or occlusion of the proximal subclavian artery, i.e., proximal to the origin of the vertebral artery. The obstruction can be bypassed by retrograde flow from the vertebral artery into the subclavian distal to the stenosis. The retrograde flow is fed either from the contralateral vertebral artery or from the carotid system via a posterior communicating artery to basilar artery to vertebral artery connection, or from both of these collateral pathways (subclavian steal).14,16 Clinical symptoms are not present invariably, and may occur only during exercise of the homolateral upper extremity, which increases drainage from the intracranial blood flow.

If obstruction of a vertebral artery occurs during life, the collateral circulation can arise from the external carotid branches which anastomose with muscular branches of the upper extracranial portion of the vertebral artery. Collateral circulation also may arise from the thyrocervical and costocervical trunks.11,14,16 Under these conditions angiography may demonstrate a vertebral artery of normal caliber, filling via collaterals in the region of cervical vertebrae C1 and C2, with no vertebral artery visualized more proximally. Stenoses due to cervical spondylosis also have been reported to cause intermittent vertebrobasilar insufficiency.16

In a normal hemodynamic situation, diastolic flow in all four major cerebral vessels never reaches zero during any phase of the cardiac cycle.7,18 Reduced diastolic flow can be due to low cardiac output or increased peripheral resistance. Significant diastolic backflow is always associated with
severe aortic insufficiency. Using the Doppler technique, low diastolic flow combined with reversed flow direction is often observed in a subclavian steal situation, since peripheral resistance in the muscular arteries of an extremity at rest is high.

**Apparatus and Basic Examination Technique**

The system used was identical to that of the carotid artery Doppler, as described previously. The examination was performed with the patient in a supine position. Aquasonic 2,000 gel served as the impedance adaptation between the mucous membrane of the dorsal oropharynx and the ultrasound crystals. Flow signals, i.e., velocity signals which were correlated with flow, were detected by a 15-cm long ultrasound probe placed through the mouth between two transverse processes of the cervical spine, preferably between C3 and C4 (fig. 1). The shaft of the probe also was used to hold the tongue, so that it would not block the entrance to the oropharynx. Common carotid artery compression more than two to four cardiac cycles was used to discriminate between the vertebral and internal carotid or a branch of the external carotid artery. Monitoring was performed by stereo-earphones and a three-channel recorder and served to bring and hold the probe in a position where maximum signals were observed and where flow was toward the probe in a normal hemodynamic situation. Flow averages for more than 20 cardiac cycles were calculated with the aid of a PDP-12 digital computer triggered synchronously by the R-peak of the ECG and displayed on an oscilloscope, from which they could be stored on digital tape for recall and comparison. All functions including computer programs were controlled by footswitches, leaving both hands free for probe placement and compression maneuvers.

**Examination Procedure, Normal and Pathological Findings**

Local anesthesia of the oropharynx was accomplished with Gingicaig® spray followed by application of 5% cocaine solution. Salivation and mucous secretion were reduced, if necessary, by an intramuscular injection of 0.5 mg of atropine. An additional person was needed to operate the suction device when secretion disturbed the detection of flow signals, since moving mucous particles due to respiration could be responsible for measurement artifacts superimposed on the flow signals received from a vessel. The probe was held with the distal part in a dorsocaudal orientation and placed on the mucous membrane of the pharynx between the transverse processes of C3 and C4. Thus, the spatial relationship between vessel axis and probe was known (fig. 1). The following parameters were used in the diagnosis of hemodynamic disturbances of the vertebral arteries.

**Flow Direction**

Flow in the vertebral artery was normally directed toward the skull, i.e., toward the probe. Factitious reverse flow can be observed if an extra loop in the vertebral artery exists below the level of C2. Diastolic flow (parameter 3) can be used to discriminate between this anatomical variant and a "real" reverse flow in a subclavian steal situation.

**Amplitude of Flow Signals**

Flow signals from both vertebral arteries were symmetrical if both vessels were of approximately equal caliber. Differences in signal amplitude of at least 50% could indicate a weaker vertebral artery on one side due to hypoplasia or severe stenosis. These anatomical entities must be distinguished from low flow signals due to non-optimal probe position. Thus, additional measurements between more proximal or distal transverse processes were needed to confirm a diagnosis. Stenosis or hypoplasia also was more difficult to diagnose when signals from both vertebral arteries were weak. A missing vertebral artery due to aplasia or occlusion was likely to exist if no vessel independent from the carotid artery was found. Also, no vertebral artery was found when the external carotid artery fed the distal extracranial part of the vertebral via its muscular branches while the proximal vertebral segment was missing or occluded.

**Diastolic Flow**

Diastolic flow in all extracranial cerebral vessels never reached zero in a person with normal cardiac output and no cardiac failure or lesion (particularly stenosis or insufficiency of the aortic valve). If in the absence of a cardiac abnormality flow reached zero during any phase of diastole, then high peripheral resistance (due to increased intracranial pressure, local high-grade stenosis distal to the measurement location, or general diffuse arteriosclerosis) or a stenosis proximal to the measurement point could be postulated. The diagnosis of subclavian steal was supported by the presence of low diastolic flow combined with reverse flow, thus distinguishing the steal situation from an extra loop of the vertebral artery with pseudoreversal flow (see parameter 1).
Reaction of Flow on Common Carotid Artery Compression

This test was used to locate the vertebral artery and to judge the function of the posterior communicating arteries. It was performed on the homolateral and contralateral common carotid arteries. Normally, no change in the vertebral artery flow was observed, or an increase occurred. The former indicated that the vessel under the probe was independent of the particular carotid artery perfusion, while the latter demonstrated that the posterior communicating artery homolateral to the compression was also functioning. If a large increase (easily visible on the recorder) follows carotid artery compression, then a shunt from the intracranial portion of the carotid artery is likely to be present, indicating a dominant posterior communicating artery, a large persistent primitive trigeminal artery, or other verteobasilar anastomoses, or reduced blood pressure in the vertebral artery under observation. If a dramatic decrease in signal occurred under the compression maneuver, a subclavian steal situation could be postulated, in which blood from the carotid arterial system under compression is being shunted down the vertebral artery being examined to bypass the subclavian stenosis. In this situation, however, one must be sure measurements are being taken from the vertebral artery, rather than a posterior branch of the external carotid artery. A blood pressure difference of more than 15 mm Hg between the two arms in these circumstances supports the diagnosis of subclavian steal. A partial flow decrease in the presence of a subclavian steal indicates that the stenosis was bypassed by both the contralateral subclavian and the intracranial portion of the particular carotid artery.

Results

Vertebral artery Doppler was used in 90 patients with symptoms of cerebrovascular insufficiency or reduced perfusion of an upper extremity, usually prior to angiography, when performed. Forty-two patients underwent angiography of the aortic arch and its extracranial cerebral vessels, and no difference in diameter between the homolateral vertebral artery. After surgical correction of the stenosis, physiological flow direction could be demonstrated by Doppler. In two patients retrograde vertebral flow was again observed on the second and third postoperative days, respectively. Suspicion of rethrombosis was angiographically verified and subsequently corrected by a second operation.

Demonstration of Typical Cases

Case 1: Normal Vertebral Artery Perfusion

Figure 2 shows the findings in a 54-year-old patient with a history of myocardial infarction due to multiple coronary artery lesions (demonstrated angiographically) and minor symptoms of a stroke in the right hemisphere. Doppler examination of the carotid and vertebral arteries was normal. Vertebral arteries were clearly detectable in the oropharynx and showed normal flow direction toward the skull. Flow amplitude was symmetrical and diastolic flow was well above zero in all phases of the cardiac cycle. A minor increase of flow was observed in both vertebrales on compression of the homolateral or contralateral common carotid artery, only detectable with stereo-earphones, indicating both posterior communicating arteries were functioning. Angiography demonstrated perfect filling of all extracranial cerebral vessels, and no difference in diameter between the left and right vertebral artery was seen.

Case 2: Missing Left Vertebral Artery

Figure 3 demonstrates the findings in a 55-year-old woman who had multiple vascular lesions with intermittent claudication in the left leg, vertigo during dorsiexion of the neck, amaurosis fugax in the right eye, and clumsiness and hypesthesia in the left arm. Multiple abdominal bruits and bruits over both carotid bifurcations could be auscultated. Carotid artery Doppler revealed high-grade stenosis or occlusion of the right internal carotid artery between the bifurcation and the origin of the ophthalmic artery. Doppler examination of the dorsal neck vessels showed normal perfusion in the right vertebral artery with minor increase of flow under compression of the left common carotid artery (left posterior communicating artery was functioning). No vessel independent from carotid artery compression was found in the left oropharynx and suspicion of a missing left vertebral artery due to occlusion or aplasia was raised. Angiography

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A missing vertebral artery was diagnosed in seven patients and angiographically verified in five. Correct diagnosis was made in 82% of the cases, and 90% reliability resulted in those cases with subclavian steal, missing vertebral artery, and normal findings.

Vertebral Artery Doppler Compared to Angiography

Findings of the 42 angiograms are correlated with the Doppler results in table 1. Eleven subclavian steal situations (four right-sided and seven left-sided) and eight vertebral artery obstructions (five occlusions or aplasia, two stenoses, and one kinking) showed pathological Doppler parameters, while in 15 patients both Doppler results and angiograms revealed undisturbed hemodynamics. In five patients pathological Doppler results (one with findings of subclavian steal, two of aplasia or occlusion, and two of stenoses) were not confirmed by angiography, while in three patients Doppler results were normal in spite of the angiographically verified morphological lesions (one aplasia or occlusion, and two severe stenoses). Correct diagnoses were made in 82% of the patients (table 1).
Figure 2. Normal findings in a 54-year-old patient (Case 1). Flow signals from both vertebral arteries were symmetrical, with diastolic flow well above zero in all phases of the cardiac cycle. Angiography showed intact extracranial cerebral vessels (retouched for emphasis). $v =$ velocity (flow) signals, $t =$ time, $I =$ uncalibrated unit, $c =$ phase of carotid artery compression maneuvers, above baseline = physiological flow direction.

demonstrated right internal carotid artery occlusion, as well as a normal right and a missing left vertebral artery.

Case 3: Subclavian Steal With Left Subclavian Artery Occluded

Figure 4 shows the preoperative findings in a 45-year-old patient with hyperlipidemia and nicotine abuse as risk factors, who suffered from easy fatigability of the left arm combined with vertigo when working with her left arm. No pulse was present in the left forearm. Blood pressure was 110/75 mm Hg in the right arm and 90/75 mm Hg in the left arm. Doppler examination showed normal perfusion of both carotid arteries, and both vertebral arteries were clearly detectable in the oropharynx. The right vertebral showed strong perfusion in the physiological direction with an increase of flow on homolateral or contralateral common carotid artery compression, indicating both posterior communicating arteries were functioning. Reverse flow and reduced diastolic flow were detected in the left vertebral, with a small decrease of flow on common carotid artery compression maneuvers, which implied that collateral circulation originated not only from the contralateral subclavian but also from the intracranial portions of both carotid arteries. The subclavian steal was angiographically confirmed by demonstration of a proximal occlusion in the left subclavian artery and delayed retrograde filling of the left vertebral artery, which subsequently filled the distal sub...
FIGURE 4. Preoperative findings in a 45-year-old patient with subclavian steal (Case 3). Both vertebral arteries were easily detectable in the oropharynx, the right one with strong flow toward the skull and the left one with flow away from the brain and a decrease of flow on homolateral and contralateral common carotid artery compression prior to operation. Abbreviations as in figure 2. Arrow = right and left vertebral arteries (main vessels retouched for emphasis).

clavian artery. Endarterectomy of the left subclavian artery was performed. Measurements on the second postoperative day revealed a perfusion situation similar to that preoperatively. Suspicion of rethrombosis was confirmed by angiography.

Discussion

Vertebral artery Doppler as a noninvasive and fast examination method allows detection of major hemodynamic disturbances in the vertebral arteries, such as subclavian steal or absent vertebral artery due to aplasia or occlusion, with about 90% reliability. Large asymmetries in perfusion by Doppler are more difficult to interpret because it is not always possible to bring and hold the ultrasound probe in an optimal position on both sides. Diagnosis of vertebral artery stenosis or hypoplasia by Doppler, therefore, is less reliable than the other categories just mentioned. In our series, overall accuracy dropped to 82% when we attempted to diagnose stenosis or hypoplasia in addition to normalcy, subclavian steal, or missing vertebral artery. Pharyngeal reflexes, secretion of saliva and mucous despite local anesthesia and parasympathetic blockade with atropine, as well as a restless patient interfere with measurements of flow signals and may be responsible for false diagnoses.

Measurements in the oropharynx with the ultrasound probe in a dorsocaudal orientation are more reliable than those in the region of the mastoid. The spatial relationship between probe and vessel axis is better known and flow direction can be used as a diagnostic parameter. Furthermore, less tissue is traversed by the ultrasound waves in the oropharynx, and the vertebral arteries, therefore, were detectable in every patient of our series. This is in contrast to the less reliable mastoid detection of the vessel in our experience. The latter may be useful in patients with collateral branches from the external carotid artery feeding via muscular branches into the upper portion of the vertebral, while the proximal segment of the vessel below the level of C2 is missing or occluded and therefore not detectable in the transoral approach. Normal Doppler findings, however, occurred in one patient with a missing vertebral artery on the angiogram. The vessel being tested was clearly independent of the carotid arterial system and probably represented an artery originating from the costocervical or possibly thyrocervical trunk.

A redundant loop of a vertebral artery below C2 can mimic reverse flow, but may be distinguished from a subclavian steal situation not only by a lack of blood pressure difference between both arms, but also by normal diastolic flow, while in steal situations diastolic flow was observed to be less than one recorder unit, due to high peripheral resistance in the muscular arteries of the extremity at rest. In one patient of our series, however, subclavian steal was diagnosed and was not present angiographically in spite of reverse flow direction and low diastolic flow by Doppler. High peripheral resistance in the distal vertebral artery combined with an extra loop in the measurement region was probably the cause of this false-positive diagnosis.

Carotid artery compression over two to four cardiac cycles is needed to differentiate the vertebral from the internal carotid or branches of the external carotid artery, and to test the function of the posterior communicating arteries of the circle of Willis. It is not without danger and should be performed only by a trained person, but it can be justified in most patients because of the low rate of risk of minor complications. The vertebral artery compression test of Kendell has not proved to be of any value in our procedure, since it can be performed only in patients with a thin neck and does not help to discriminate between vertebral and other extracranial vessels.

Vertebral artery Doppler should be performed in the same session, subsequent or prior to carotid artery Doppler, to judge hemodynamics in all feeding vessels of the intracranial vascular system as well as the function of the circle of Willis. The latter is particularly helpful in those cases with severe obstruction of one or several extracranial arteries.
Not only is the obstruction diagnosed but the compensating mechanism is evaluated as well and the result can help to select the surgical approach in a given patient, if endarterectomy is to be performed.

Postoperative follow-up examinations in patients operated on for a subclavian steal help to evaluate the effect of the intervention on cerebral hemodynamics. Reverse flow direction in the involved vertebral artery reverted to normal by Doppler immediately after surgery in all 11 patients in the subclavian steal group. In those cases with a flow decrease on common carotid artery compression maneuvers prior to surgery, a minor flow increase was observed postoperatively, corresponding to normal posterior communicating artery function with no residual steal from an intracranial portion of a carotid to the vertebral artery. Recurrence of abnormal vertebral flow direction on the operated side was observed in two patients on the second and third postoperative days. This not only supported the diagnosis of rethrombosis suspected from blood pressure measurements, but also localized the obstruction as proximal to the origin of the vertebral artery. The localization of a stenosis in a subclavian artery is also important when blood pressure measurements between the upper extremities differ significantly but typical subclavian steal symptoms are absent. If reverse flow in a vertebral artery is detected by Doppler, angiography and surgery can be performed as quickly as warranted clinically. Vertebral artery Doppler can also reveal subclavian steal hemodynamics without cerebral symptoms in those patients with severe bilateral subclavian artery stenosis, e.g., one stenosis proximal and the other distal to the vertebral artery origin, by the presence of retrograde flow in one vertebral artery, while blood pressure measurements in both arms are equal.

Carotid and vertebral artery Doppler as noninvasive procedures do not replace angiography. These procedures allow detection of obstructions in the extracranial carotid and vertebral arteries with a high degree of reliability, although without exact localization. They are quickly performed (average, 45 minutes for both examinations), and facilitate procedures do not replace angiography. These procedures allow sure measurements in both arms are equal.

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