be safe, easily accomplished when one knows the technique, and results in no neuropathological changes at the site of the omental transposition.

Note
(See Letter to the Editor: Omental Transposition To Human Brain, p. 272.)

References

Cardiac Cycle-Dependent Alternating Flow in Vertebral Arteries with Subclavian Artery Stenoses
Gerhard-Michael von Reutern, M.D., and Léandre Pourcelot, M.D., Dr.(Eng.)

SUMMARY  Continuous-wave Doppler sonography is a reliable method for detecting severe subclavian stenosis and occlusion as well as subclavian steal. Intermediate stages leading to subclavian steal can also be detected. These are characterized by a cardiac-phase-dependent alternating flow direction in the vertebral artery. Some cases of proximal subclavian or proximal vertebral artery stenosis produce a systolic deceleration of flow in the vertebral artery. Stenosis and occlusion of the subclavian artery as well as stenosis of the subclavian and vertebral arteries can be distinguished. The pulse curve changes described can be reversed by a vascular bypass. Alternating flow direction or systolic deceleration of flow in the radial artery could also be observed or induced in a iatrogenic model using Cimino's a-v fistula in the arm in patients on dialysis.

The results in beginning subclavian steal situations can be applied in principle to other collateral circulations, and in particular to the hemodynamics in the region of watersheds.

REVERSE FLOW in the vertebral artery resulting from occlusion of the proximal subclavian artery (subclavian steal) which was first described in an angiographic study, can be demonstrated by transcutaneous Doppler sonography. Since occlusion of the proximal subclavian artery usually develops slowly with progression of arteriosclerotic stenosis, it is to be expected that intermediate, previously undescribed, flow patterns of forward and reverse flow will be found in flow studies of the vertebral artery. The results presented in this paper show it is possible to demonstrate such intermediate forms (incomplete steal) by means of Doppler sonographic examination of the subclavian and vertebral arteries. Characteristic changes are also described in patients with high-grade proximal stenosis of the vertebral artery, which could not previously be differentiated with certainty from hypoplasia and occlusion.

Material and Methods
The transcutaneous semiquantitative measurement of velocity and direction of blood flow was carried out with a directional continuous wave Doppler device, "Débitimètre Ultrasonique Delalande," at a frequency of 4 MHz. The Doppler pulse curves and the ECG were simultaneously registered on a direct-writing recorder (Cardirex 4-channel, Siemens and Brush 2-channel).

Recordings of flow in the subclavian artery are made in the supraclavicular fossa. Medial or lateral alignment of the probe allows examination of the proximal or distal portion of the vessel. The vertebral artery is examined at the level of the atlas slope, but it is not possible to determine by transcutaneous examination whether the afferent (flow to probe) or efferent (flow away from probe) section of the atlas slope is reached by the ultrasonic beam. The upward or downward direction of the pulse curves in relation to the zero line gives no clear indication of forward or reverse flow in this artery. This can only be determined by functional tests. With reverse (armward) flow, raising peripheral resistance to flow (compression of the upper arm or closure of the fist) causes deceleration of flow followed by raised flow velocity in the vertebral artery (postischemic hyperemia). With forward flow in the vertebral artery upper arm compression usually causes no significant change in flow velocity. The pulse curves of the vertebral artery for antegrade and retrograde flow, which show distinct differences, are illustrated in figure 1A and 1D, together with the effect caused by upper arm compression. In this study, for the purpose of simplification, the Doppler device was
pole to show an upward deviation of the Doppler pulse curve in relation to the zero line for forward flow. The differentiation of the vertebral artery from the occipital and other neck arteries has been described previously.\textsuperscript{1}

In order to measure the temporal relationship of Doppler pulse curves to the ECG, 10 disturbance-free pulse curves were averaged by measuring the latency between the R-peak and 6 to 10 defined points of the Doppler pulse curve, including in each case the arise point of systolic acceleration and the 10% and 90% arising and falling values.

Eighty-five patients have been found with proximal obstructions of the subclavian artery with complete reversal of vertebral flow. Angiographic examination was carried out in 34 of these patients confirming the findings in every patient.

Results

I. Doppler Sonography

Since the angle of transmission, particularly in the region of the atlas slope, is unknown, the amplitude reduction of the flow velocity curve of the vertebral artery is not a reliable sign of obstruction to flow. On the other hand, in the presence of high-grade stenosis of the subclavian or vertebral artery, we found typical changes in flow patterns as shown in figure 1. The development from proximal subclavian stenosis to occlusion, for example, produces changes in the pulse curves of the ipsilateral vertebral artery occurring in the order in which they are presented in figures 1B to D.

The well-known pulse curves in normals and those resulting from complete reversal of flow in the vertebral artery (subclavian steal, fig. 1D) will first be discussed, and then the pulse curves of partial reversal of flow or intermediate forms (fig. 1 B, C).

1) Normal Flow Patterns of Vertebral and Subclavian Arteries

The Doppler pulse curve of the subclavian and vertebral arteries of a healthy subject and the relationship to the ECG are shown in figure 2. The R wave of the ECG denotes the onset of ventricular systole and the end of the T wave marks, approximately the beginning of diastole. The flow pattern of the subclavian artery shows a steep systolic wave and shortly after the onset of diastole a brief reverse flow phase. During later diastole no significant flow is present. In contrast to this, the normal pulse curve of the vertebral artery with forward flow shows less amplitude modulation. The decrease in late systole and in diastole is continuous and during the whole of diastole there is forward flow. The differences in the pulse curves are due to the low peripheral flow resistance in the vertebral artery which supplies the brain and the high resistance in the subclavian artery supplying skin and muscle.\textsuperscript{1, 10, 12, 13} The latency of the arise point and the peak of the flow velocity curve of the vertebral artery are approximately 10 msec longer than those of the subclavian artery (pulse wave propagation velocity about 10 mm/ms). It is dependent on the pulse frequency and the state of the vessel walls.

![Figure 1: Development of subclavian steal: Doppler pulse curve from the vertebral artery with forward flow (A), systolic deceleration (B), alternating flow (C), complete reversal of flow (D), in each case occurring on the side of subclavian occlusion. The horizontal bars above the pulse curves indicate the duration of the ipsilateral upper arm compression. The continuous straight line corresponds to zero flow velocity. The apparatus was so adjusted that an upward deviation of the pulse curve in relation to the zero line indicated forward flow. Ordinate: calibration signal of apparatus = 30 cm/sec.]

![Figure 2: Doppler pulse curve of the subclavian and vertebral artery from a healthy 30-year-old man, and their temporal relationship to the ECG. A = the onset of R-wave, B = the arise point of the systolic wave in the subclavian artery, C = the end of the T-wave which indicates approximately the beginning of diastole.]
2) Reverse Flow in Vertebral Artery with Proximal Occlusion of Subclavian Artery

The pulse curve in figure 1D is characteristic for completely reversed flow in the vertebral artery, which is usually due to complete occlusion of the subclavian artery. The flow direction is reversed during systole and diastole. Since the vertebral artery contributes to the blood supply of the arm, the flow pattern is changed. The amplitudes vary considerably from patient to patient. In a typical patient the arise points of the systolic wave lie near the zero-line, due to the higher peripheral resistances to flow in the arm vessels than in the cerebral vessels.

For an analysis of the temporal relationship between the cardiac cycle and Doppler pulse curves the latter were averaged using the R-wave of the ECG as a trigger signal. This is shown in figure 3 for a patient with complete occlusion of the right subclavian artery (diagram of his vessels is seen in fig. 4).

A comparison of the arise point and peak of the right and left subclavian arteries shows a definitely longer latency on the side of the collaterally supplied subclavian artery as a result of the increased distance traversed by the pulse wave. In this patient the difference in latency of the arise points of the systolic wave in the subclavian arteries measured 41 msec. The difference in latency of the arise point of the systolic wave of the vertebral arteries is shorter, in this case 18 msec. This difference can be explained by the shorter distance between the points of measurement (atlas slopes of the vertebral arteries). The reason for the different latencies of the systolic peak of the vertebral and subclavian arteries on the unaffected (left) side is not clear (see also figs. 5, 6). Possible causes are a compensatory increase in flow with slight turbulence or transmission conditions and flow anomalies in a vessel loop. In addition, the latency values of the systolic peaks are more variable potentially resulting in a greater statistical error.

3) Alternating Flow in Vertebral Artery with Proximal Stenosis of Subclavian Artery

Figure 1C shows a cardiac-phase-dependent change in the direction of flow in the vertebral artery, from reverse to forward flow. This flow pattern is found with high-grade stenosis of the ipsilateral subclavian artery (fig. 7). It could be constantly elicited on examination with various probe positions and was not an artifact due to superimposed venous or arterial flow.

Figure 5 shows the latency measurements in a patient with severe left-sided subclavian stenosis. The peak velocities of...
both vertebral arteries have about the same latency. On the stenosed side, however, the direction of flow at this instant is reversed. In diastole there is forward flow in both arteries. On the stenosed side there is an acceleration of flow in a forward direction at the onset of the systolic pulse wave. After a short time, however — in this example after approximately 30 msec — deceleration and finally reversal of flow (downward movement of pulse curve) occurs. The initial forward acceleration is often of very short duration and it is sometimes difficult to distinguish from normal pulse curve irregularities. It must, however, be taken into consideration for the measurement of the latency period.

The comparison of the pulse curve of the subclavian artery shows, in contrast to the example in figure 3, no delay in the latency of the arise point of the systolic wave on the stenosed side. The flow velocity pattern of the collaterally filled and proximally severely stenosed or occluded subclavian artery are, however, in other respects comparable with decreased amplitude, delay in the latency period of the systolic peak and absence of reverse flow at the beginning of diastole. When there is alternating flow in the vertebral artery the relationship of cerebral to armward flow may be altered by changes in the peripheral resistance in the ipsilateral arm (upper arm compression and closure of fist — see bar over pulse curve in fig. 1C). This may cause a temporary complete reversal of vertebral artery flow in the phase of reactive postischemic hyperemia of the arm.

4) Systolic Deceleration of Flow in Vertebral Artery with Proximal Stenosis of Subclavian Artery

If proximal stenosis of the subclavian artery produces a smaller hemodynamic effect than that shown in the example in figure 5, there will be no systolic reversal of flow direction in the ipsilateral vertebral artery, but only a deceleration of flow (dip in the pulse curve — see also fig. 9). The systolic wave peak of the patent vertebral artery coincides approximately with the bottom of the systolic dip on the stenosed side. In these instances the flow patterns from the subclavian artery do not differ significantly from those found in alternating flow in the vertebral artery.

5) Systolic Deceleration of Flow in Vertebral Artery with High-grade Proximal Stenosis of Vertebral Artery Itself

At the beginning of our Doppler investigations of the vertebral system we believed that with increasing proximal stenosis of the vertebral artery a decrease in the pulse curve amplitudes would occur (significant amplitude reduc-
tion = difference between the two sides greater than 75%), or that finally, as a result of the extremely reduced flow, no Doppler signals could be registered. Contrary to our expectations, in instances of significantly reduced or undetectable flow, angiographic examination very rarely showed high-grade proximal stenosis of the vertebral artery. This causes flow patterns comparable to those found in proximal subclavian stenosis. The reason is that in proximal stenosis of both the vertebral and subclavian arteries there is considerable upstream obstruction to flow. Figure 6 shows a typical situation: the pulse curves from the vertebral artery resemble those which may be found from subclavian stenosis (see also fig. 9). For the subclavian arteries, on the other hand, a comparison of the 2 sides shows no essential difference, there being thus no indication of an impediment to flow in these arteries.

II. Correlation of Doppler and Angiographic Findings

Table 1 shows the Doppler results correlated with the findings of angiography. Alternating flow in the vertebral artery with varying degrees of flow reversal was found most frequently in high-grade subclavian stenosis and more rarely in occlusion of the subclavian artery. In 3 patients with subclaval...
diastole) before operation.

Complete reverse flow, alternating flow and systolic deceleration of flow in the vertebral artery (systolic flow deceleration) and the subclavian artery in high-grade stenosis of the vertebral artery. (In parentheses, the number of patients examined angiographically). The Doppler diagnoses were confirmed without exception. In two cases of alternating flow, high-grade proximal subclavian stenosis was associated with stenosis of the subclavian artery. (For further explanation see text.)

Table 1: Frequency of Doppler diagnoses with complete reverse flow, alternating flow and systolic deceleration of flow in the vertebral artery. (In parentheses, the number of patients examined angiographically). The Doppler diagnoses were confirmed without exception. In two cases of alternating flow, high-grade proximal subclavian stenosis (systolic flow deceleration) was associated with stenosis of the subclavian artery. (For further explanation see text.)

<table>
<thead>
<tr>
<th>Pulse curve of the Vertebral A.</th>
<th>n</th>
<th>Occlusion Subclavian A</th>
<th>Stenosis Subclavian A</th>
<th>Stenosis Vertebral A.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete reverse flow</td>
<td>85 (34)</td>
<td>76 (30)</td>
<td>9 (4)</td>
<td>0</td>
</tr>
<tr>
<td>Alternating flow</td>
<td>42 (15)</td>
<td>5 (2)</td>
<td>37 (13)</td>
<td>2 (2)</td>
</tr>
<tr>
<td>Systolic flow deceleration</td>
<td>27 (9)</td>
<td>0</td>
<td>15 (4)</td>
<td>12 (5)</td>
</tr>
</tbody>
</table>

Figure 9. Postoperative normalization in Doppler pulse curves of vertebral artery and subclavian artery in high-grade stenosis of brachiocephalic trunk. Note the pathological flow profile in the vertebral artery (systolic flow deceleration) and the subclavian artery (reduced amplitude, no reverse flow phase at the beginning of diastole) before operation.

Postoperative normalization in Doppler pulse curves of right internal and common carotid arteries and vertebral artery in complete occlusion of the brachiocephalic trunk. Before operation the internal and common carotid arteries show alternating flow and the vertebral artery complete flow reversal. Reactive hyperemia after ipsilateral compression (horizontal bar above the pulse curve) of the upper arm, completely reverses flow (A). The pulse curves become normal after aorto-subclavian by-pass operation.

III. Restoration of Normal Pulse Curves by Vascular Surgery

Follow up observations proved that the pulse curves illustrated in figure 1B and C were, in fact, intermediate forms. In a patient with high grade subclavian stenosis which had caused alternating flow in the vertebral artery a carotid-subclavian by-pass operation was performed. The pulse curves from the vertebral and subclavian arteries subsequently returned to normal. In another patient with systolic deceleration of flow in the right vertebral artery due to high grade stenosis of the brachio-cephalic trunk, similar postoperative normalization was seen (fig. 9).

In a patient with occlusion of the brachio-cephalic trunk we observed alternating flow in the homolateral common carotid artery similar to that described above in the vertebral artery of a patient with subclavian stenosis. After upper arm compression the flow was completely reversed (fig. 10 A). An aorto-subclavian by-pass operation was performed, and after the operation (fig. 10 B) physiological flow was shown to be reestablished in the carotid artery.

IV. Experimentally Induced Alternating Flow in Radial Artery

In patients on renal dialysis who have an artificial arterio-venous fistula in the lower arm the portion of the radial...
artery proximal (fig. 11 A) and distal (fig. 11 B) to the fistula may be compared to the right and left vertebral arteries. This is when the shunt also receives blood over the distal part of the radial artery supplied from the ulnar artery via the palmar arch. In this model the ulnar artery corresponds to the proximal subclavian artery. In this model, too, the pulse curve characteristics from the proximal and distal radial artery resemble those of forward flow in the vertebral artery due to the low peripheral resistance to flow. The pulse curve from the distal section of the radial artery in this situation is illustrated in figure 12 A. This pulse curve can be changed to alternating or retrograde flow by increasing compression on the ulnar artery (fig. 12 B-D). When compared to the subclavian-vertebral system this corresponds to increasing stenosis in the proximal subclavian artery.

Discussion

In the presence of occlusion of the subclavian artery the ipsilateral vertebral artery takes over the function of a collateral vessel (subclavian steal). The usual direction of flow is then reversed. In high grade stenosis of the subclavian artery there is usually not a complete reversal of flow in the vertebral artery but alternating flow dependent on the cardiac cycle. The basis for this is that the difference in pressure and the resistance to flow in the right and left subclavian-vertebral system change during the cardiac cycle. In all patients with alternating flow in the vertebral artery the latency measurement to the R-peak of the ECG showed a reversal of flow only during a part of systole, which can be explained as follows:

The hemodynamic effect of stenosis, a poststenotic fall in pressure, increases with rising flow velocity during systolic flow acceleration. It is thus understandable that the pressure gradient between the vertebral system and the poststenotic subclavian artery is only large enough to effect a reversal of the direction of flow in the ipsilateral vertebral artery at the peak range of systolic flow velocity, and not at the onset of systolic acceleration or during diastole. If the pressure gradient caused by proximal subclavian stenosis is not high enough during systole to cause a reversal of the direction of flow in the vertebral artery, only a systolic deceleration or cessation of flow may be seen. The Doppler pulse curves with systolic flow deceleration or alternating flow are, therefore, characteristic of intermediate forms leading to complete subclavian steal. It is common to them all that the watershed shifts in relation to the cardiac cycle, at times found in the region of the vertebral artery itself but shifting from the cranial direction downward and backward.

A displacement of the watershed can also occur as a result of an alteration in peripheral flow resistance. If there is alternating flow in the vertebral artery at rest it is possible to
effect displacement of the watershed toward the head with no reversal of flow by compression on the upper arm on the side of the subclavian stenosis, and displacement toward the arm i.e. complete reversal of flow due to reactive post-ischemic hyperemia (see fig. 1 C).

Figure 6 shows that high grade proximal vertebral stenosis as well as proximal subclavian stenosis may lead to systolic flow deceleration of the Doppler pulse curves of the distal vertebral artery. The hemodynamic situation in the region under examination, at the level of the atlas slope, is similar in both types. In contrast to subclavian stenosis, in vertebral stenosis no complete reversal of flow in the vertebral artery can be induced by reactive postischemic hyperemia of the arm (lowering of resistance). Moreover, the pulse curves from the subclavian artery are symmetrical, so that in typical cases there is no difficulty in differentiating between vertebral and subclavian stenosis. It is only in combined vertebral and subclavian stenosis that such problems are to be expected.

Alternating flow in the vertebral artery usually correlates with angiographic evidence of high-grade subclavian stenosis. In occlusion of the subclavian artery, which usually shows complete reversal of flow, alternating flow with minimal forward flow in diastole was a rarer finding. In two patients it was due to aortic valve insufficiency. It is possible to differentiate between stenosis and occlusion of the subclavian artery by measuring the latency of the arise point during systolic acceleration. A delay in latency is found only with occlusion. It is usually possible to make this differentiation without simultaneous ECG recording, since proximal stenosis of the subclavian artery leads to severe turbulence which may be conveyed to the supraclavicular fossa and be recordable there.

With alternating flow of approximately equal degrees of forward and reverse flow, the affected arteries may not be demonstrable by aortic arch angiography. In these instances patency and a beginning steal can only be proved by selective angiographic methods with simultaneous functional tests (upper arm compression and/or closure of fist).

In the hands of an experienced examiner directional continuous wave Doppler sonography is more than a simple screening method. It is often more useful than angiography for the evaluation of the hemodynamics of the extracranial cerebral vessels. The exact demonstration of the morphology of vascular changes can only be obtained with selective angiography in several planes. Aortic arch angiograms do not usually give sufficient information to supplement the Doppler diagnosis. Initial Doppler sonographic examination is followed by more precise formulation of the question at angiography, but often Doppler diagnosis is sufficiently reliable to be able to replace angiography.

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