Using directional continuous-wave Doppler sonography of the vertebral arteries, we have investigated 1,540 patients during the past 5 years. On the basis of unilateral and bilateral retrograde brachial angiograms in the same patients a total of 1,989 angiograms) we have developed sonographic criteria for demonstrating a significant increase in the peripheral resistance of both distal vertebral arteries and/or the basilar artery. All 11 cases of basilar artery stenosis of at least 60% reduction in lumen diameter (as shown by angiography) exhibited an approximately 40% or higher reduction in the sum of the modified Pourcelot indices of both vertebral arteries with respect to age-matched controls. All 3 stenoses of less than 60% reduction in lumen diameter were not detected by sonography. Even a good collateral circulation through rete mirabile anastomoses did not normalize the modified Pourcelot indices. One case of a persistent primitive trigeminal artery with thin-calibered vertebral arteries was also detected by sonography. The high percent of patients with one hypoplastic vertebral artery in the group with basilar artery stenoses indicates an increased risk for atherosclerosis of the basilar and/or distal vertebral artery in these patients. All 14 angiographically verified occlusions of the basilar artery were detected by sonographic criteria independent of the occlusion localization. Thus, we believe that directional continuous-wave Doppler sonography is a reliable technique for detecting basilar artery stenoses of at least 60% reduction in lumen diameter and basilar artery occlusions.

**Subjects and Methods**

The present article refers to 1,540 patients exhibiting typical symptoms of atherosclerotic cerebrovascular disease, but also includes cases prior to an angiographic investigation for a suspected mass lesion or a vascular malformation. Their routine work-up included the investigation of the carotid and vertebral arteries by directional c-w Doppler sonography. All of these patients underwent at least unilateral retrograde brachial angiography. Of these, we report 29 cases with stenoses or occlusions of both distal vertebral and/or the basilar arteries. All of these 29 patients were examined with c-w Doppler sonography and bilateral retrograde brachial angiography due to transient or permanent neurological deficits.

In the evaluation of Doppler findings in the vertebral arteries, we employed the criteria developed by Bödinger, von Reutern, and Freund as previously reported. With a conventional 4-MHz hand-held probe, the optimal signals of the vertebral arteries at their atlas loops and in the supravacuicular fossae were obtained by acoustic and oscillographic control.

Recently, we defined the ratio of end-diastolic to maximal flow velocity as the circulatory resistance index, which we call the modified Pourcelot index. The advantage of this parameter with respect to the index originally described by Pourcelot (1 - modified Pourcelot index) is its direct rather than inverse relation to vascular lumen area. A reduction in lumen diameter distal to the location of examination induces a decrease in the end-diastolic rather than in the systolic flow velocity and thereby in the modified Pourcelot index. Since this index is independent of the angle of insonation, it allows interindividual comparison and hence statistical analysis.

The correlation between the modified Pourcelot index and the flow volume of a vessel is not thought to be strictly proportional since factors like pulse frequency are not considered. However, the acceptable SD of this index found in controls is analogous to that of the original Pourcelot index and indicates that the modified Pourcelot index constitutes a clinically reliable parameter.

We calculated the modified Pourcelot indices of both vertebral arteries by recording their pulse curves at their atlas loops; the ratio of end-diastolic to maximal flow velocity was obtained by averaging at least 5 consecutive pulse curves for each artery. We used the
sum of both indices because the vertebral arteries constitute a functional unity via the basilar artery.

We determined the modified Pourcelot index of each vertebral artery and the sum of both vertebral indices in 326 patients without permanent neurological deficit, classified into decennial age-groups, to establish control values. Approximately half of these patients were included in the 1,540 patients referred to above and underwent (partly due to transient ischemic attacks, TIA's) at least unilateral retrograde brachial angiography with visualization of the entire basilar artery, but neither major circumscribed stenoses nor atherosclerotic irregularities were detected by angiography. Other indications for angiography were exclusion of intracranial tumors and vascular malformations. In the age-groups up to 49 years, the percent of angiographic controls was lower. In these patients without an angiographic examination, the indications for sonographic evaluation were unspécific neurologic complaints such as dizziness and nonpulsatory tinnitus, and the questions of an angioma in unilateral migraine and of extracranial carotid artery disease in cases with known diabetes mellitus or primary hyperlipidemia. There was no history of TIA's in these patients, nor were there any abnormal findings in their neurologic examinations.

A second subset of 111 patients classified into decennial age-groups was established on the basis of the sonographic diagnosis of a unilateral vertebral hypoplasia; a unilateral modified Pourcelot index of 0.00 served as the corresponding sonographic criterion. Approximately half of these patients also underwent angiography on the side of the suggested hypoplasia for reasons as stated above for the control group without major irregularities being detected. In these angiographically investigated cases, the thin-calibered hypoplastic vertebral artery filled the posterior inferior cerebellar artery (PICA) predominantly (with only flash filling of the basilar artery through the very thin segment distal to the origin of the PICA) or exclusively (ending in the PICA). In the patients not examined by angiography, Doppler sonography theoretically cannot exclude a distal vertebral occlusion—e.g., distal to the origin of the PICA. However, the indications for sonographic evaluation of this latter subset of patients, who were not investigated with angiography, are the same as those in the control group. On this basis, we considered unilateral atheromatous vertebral disease highly unlikely to cause the observed unilateral modified Pourcelot index of 0.00, and we assumed the cause to be a thin-calibered vertebral artery mainly or exclusively supplying the PICA, i.e., a vertebral hypoplasia, instead.

All 1,540 patients in this study—except approximately half of the controls as stated above—underwent unilateral or bilateral retrograde brachial arteriography with visualization of the basilar artery. Angiography was always preceded by Doppler sonography. A total of 1,989 retrograde brachial arteriograms were performed in this study. In 905 patients (1,093 angiograms), the preceding Doppler studies of the carotid and the vertebral systems revealed normal findings. In the remaining 606 patients (838 angiograms) with underlying abnormal Doppler findings, angiography was performed in approximately 80% due to suggested extracranial carotid artery disease (right retrograde brachial angiography), in about 5% due to severe intracranial carotid artery disease, in almost 5% due to proximal vertebral artery disease including the subclavian-steal syndrome, and in approximately 10% due to multiple extracranial and intracranial stenotic lesions. In 4 cases with basilar artery occlusions, we performed percutaneous left carotid angiography since right retrograde brachial arteriography did not reveal the right posterior communicating artery.

In the angiographic evaluation of basilar artery disease, we employed the division into thirds as described by Archer and Horeinstein: the proximal third between merging of both vertebrels and the origin of the anterior inferior cerebellar arteries, the middle third to the superior cerebellar arteries, and the rostral third to the posterior cerebral arteries. The degree of stenosis was calculated on the basis of lumen diameter.

Results

Controls

The modified Pourcelot indices of the vertebral arteries and the sum of both vertebral indices (as functional unity) were determined in 326 control patients without permanent neurological deficit. In Figure 1, these results are shown according to decennial age groups. With increasing age, there is a decrease in the relative end-diastolic flow velocity. The modified Pourcelot index of one vertebral artery did not fall below 0.10 (Figures 1 B, 2).

In cases of a unilateral modified Pourcelot index of 0.00, we suggested a hypoplasia of the corresponding vertebral artery; in Figure 3, the results in 111 patients with the angiographically proven or sonographically suggested diagnosis of unilateral vertebral hypoplasia are listed in decennial age groups. It is notable that the corresponding nonhypoplastic vertebral artery exhibited a lower modified Pourcelot index than the sum of both indices in cases with no vertebral hypoplasia.

In the 326 control cases of Figure 1, the modified Pourcelot indices showed differences of less than 10% between both vertebral arteries in 20% of all patients; in 28%, the modified Pourcelot index of the right vertebral artery preponderated that of the left by 10% or more, while in 52%, the index of the left vertebral artery exceeded that of the right by at least 10%. In the 111 cases with unilateral vertebral hypoplasia (Figure 3), the right vertebral artery was hypoplastic in 57% and the left in 43%.

Stenoses of the Basilar Artery

Fourteen cases exhibited a basilar artery stenosis upon angiography—10 in the proximal third, 3 in the middle third, and 1 patient along the entire course of the basilar artery. For comparison of the sonographic and angiographic findings, we calculated the reduction of the sum of the modified Pourcelot indices of the
vertebral arteries on the basis of the age-matched controls. We employed the values of Figure 1 for comparison as long as the modified Pourcelot index of one vertebral artery was not 0.00. In those cases with a unilateral modified Pourcelot index of 0.00 (10 of 14 cases), the values of Figure 3 served as a control. The separate comparison of the cases with a sonographically suggested unilateral vertebral hypoplasia to controls with angiographically proven unilateral vertebral hypoplasia was necessary since otherwise the reduction of the sum of the modified Pourcelot indices with respect to controls would be overestimated.

All 3 stenoses with a reduction in lumen diameter of less than 60% by angiography (2 in the proximal and 1 in the middle third) were not detected using the sum of the modified Pourcelot indices of the vertebral arteries. Despite a residual end-diastolic flow component, all 11 stenoses with at least a 60% reduction in lumen diameter (8 in the proximal and 2 in the middle third, and 1 case along the entire course of the basilar artery) showed an approximately 40% or higher reduction in the sum of the modified Pourcelot indices. This reduction is at least 2 SD, and in 10 of 11 cases >3 SD, with respect to the mean of the age-matched control group.

**Figure 1.** A Age dependency of the modified Pourcelot index of the vertebral arteries. The modified Pourcelot index is defined as the ratio of end-diastolic to maximal flow velocity. (Mean, gray; SD, white.) B Side differences between the modified Pourcelot indices of the vertebral arteries. (Mean, gray; SD, white.) The large SD indicates the usefulness of employing the sum of both vertebral indices in the evaluation of the circulatory resistance. C Age dependency of the sum of the modified Pourcelot indices of the vertebral arteries. (Mean, gray; SD, white.)
FIGURE 2. Pulse curves of both vertebral arteries; 57-year-old healthy individual. 0, zero baseline; d, end-diastolic flow velocity; abscissa, time; ordinate, relative flow velocity in the vertebrals; l, left; r, right. No absolute values are given on the ordinate because the amplitude of the flow signal depends on the angle of insonation. The modified Pourcelot index constitutes an angle-independent parameter.

The original sonographic and angiographic data can be provided on request. We did not find any patient with a reduction in the summed modified vertebral Pourcelot indices of 2 SD or more with respect to age-matched controls who had normal angiographic findings.

In one patient with an angiographically proven unilateral vertebral hypoplasia and a basilar stenosis in the proximal third exceeding a 70% reduction in lumen diameter, we found a modified Pourcelot index of 0.13 (Figure 4) in the hypoplastic vertebral artery. Angiography revealed rete mirabile anastomoses between the inferior and superior cerebellar arteries at the site of the vertebral hypoplasia, which explains the lower peripheral resistance. However, the sum of the modified vertebral Pourcelot indices was reduced by $> 3$ SD with respect to the mean of the corresponding control group (employing the values of Figure 1 for comparison).

It is notable that 11 of 14 patients with basilar artery stenosis showed unilateral vertebral hypoplasia; angiography revealed no major atherosclerotic irregularities in the vertebral artery that was judged hypoplastic and showed no connection between the hypoplastic vertebral and the basilar artery in 10 of these 11 cases. One case of a persistent primitive trigeminal artery (Type I according to Saltzman and Lie) with thin-calibered basilar and vertebral arteries fulfilled the sonographic criteria of increased peripheral resistance as well. The modified Pourcelot indices were 0.07 (right) and 0.14 (left), reduced by $> 3$ SD with respect to the mean of the age-matched control group.

**Occlusions of the Basilar Artery**

All 12 patients with an occlusion of both distal vertebral arteries and/or the proximal third of the basilar artery (Figure 5) showed a modified Pourcelot index of 0.00 with no end-diastolic flow component in both vertebral arteries (10 patients) or no detectable Doppler frequency shift (2 patients). The latter 2 cases date back to the initial phase of the study, when we had less experience in the detection of weak Doppler signals.

One occlusion of the basilar artery between the middle and rostral thirds exhibited a residual diastolic flow component in the sonographic evaluation of the vertebral arteries. However, the sum of the modified Pourcelot indices was reduced by $> 3$ SD with respect to the mean of the age-matched control group. One additional basilar artery occlusion at this location was sonogra-
FIGURE 4. Doppler sonographic findings of the vertebral arteries; stenosis of the basilar artery of > 70% reduction in lumen diameter in its proximal third. On the right side, vertebral artery hypoplasia with rete mirabile anastomoses between the PICA and the superior cerebellar artery. 0, zero baseline; d, end-diastolic flow velocity; l, left; r, right.

Phically detected due to an absent diastolic flow component in both vertebral arteries (modified Pourcelot indices of 0.00).

In all of the sonographic follow-up examinations we have performed in cases of basilar artery occlusions, the modified Pourcelot indices of the vertebral arteries did not return to normal values with respect toagematched controls.

Discussion

Previous researchers have reported the sensitivity and specificity of directional c-w Doppler sonography in identifying normal vertebral arteries, moderate or severe stenosis and occlusion at the origin of the vertebral arteries, the subclavian-steal syndrome, and hypoplasia or distal stenosis and occlusion of one vertebral artery.17 Recently, we demonstrated the reliability of Doppler sonography in detecting severe stenosis and occlusion of both distal vertebral arteries and/or the proximal basilar artery.6 In this study, the correlation of directional c-w Doppler sonographic findings with the results of almost 2,000 retrograde brachial angiograms done on more than 1,500 patients indicates that the technique is also sufficient for identifying stenoses of the basilar artery with at least a 60% reduction in lumen diameter. The only prerequisites are quality recordings of the vertebral pulse curves to calculate the modified Pourcelot indices.

All 26 patients with basilar stenoses of at least a 60% reduction in lumen diameter (11 cases), thin-calibered

FIGURE 5. Doppler sonographic findings of the vertebral arteries; occlusion of the proximal third of the basilar artery. 0, zero baseline; l, left; r, right. The relative flow velocity of both vertebral arteries fall to 0 (arrows) prior to the initiation of the following pulse curve.
vertebral arteries (1 case of a persistent primitive trigeminal artery), and occlusions of the basilar artery in any segment (14 cases) exhibited an approximately 40% or higher reduction in the sum of both vertebral modified Pourcelot indices with respect to age-matched controls. Even a decrease in the peripheral resistance by *rete mirabile* anastomoses between the posterior inferior and superior cerebellar arteries did not normalize the summed circulatory index.

All cases of basilar artery stenoses and occlusions were diagnosed prospectively by sonography if both vertebral arteries showed either a modified Pourcelot index of 0.00 or no detectable Doppler frequency shift. The basilar stenoses and occlusions with a residual end-diastolic flow component of the vertebral pulse curves by sonography were diagnosed retrospectively.

The lack of false-positive cases among the almost 2,000 brachial angiograms suggests that the technique is highly specific for identifying distal vertebral or basilar disease of at least a 60% reduction in lumen diameter.

We suggest that a reduction of the sum of both vertebral modified Pourcelot indices by >3 SD with respect to age-matched controls—especially bilateral absence of an end-diastolic flow component—is highly suggestive of substantial basilar artery disease; a reduction by 2 SD indicates, in our opinion, the necessity for further evaluation depending on the clinical symptoms. The modified Pourcelot indices must be compared with age-matched controls due to the age-related decrease of this parameter. The figures provided in the present study relate strictly to a 4-MHz probe; under this recording condition, the control data provided can, in our opinion, be generalized to other normal populations in other laboratories. C-w Doppler sonography does not allow differentiation of the stenotic and occlusive localization in the course of the basilar artery on the basis of the extracranially recorded pulse curves.

The introduction of the modified Pourcelot index as a circulatory resistance index appears useful; in controls, we found an asymmetric distribution of the relative end-diastolic flow components in the vertebral arteries. Similar figures (26%, 32%, 42%) were published by Krayenbühl and Yasargil with respect to angiographic lumen dieters.

The high percent of patients with unilateral vertebral hypoplasia in the group with basilar artery stenoses indicates an increased risk for atherosclerotic lesions of the basilar and/or the distal nonhypoplastic vertebral arteries in these cases.

There are no explicit statements about the lowest limit for detecting an intracranial stenosis of both distal vertebral arteries or the basilar artery. However, the minimum degree of stenosis of 60% found in our series corresponds well with the lowest degree of stenosis that induces hemodynamic changes in extracranial and intracranial carotid artery disease.

While occlusion of the basilar artery has for many years been generally considered a serious event, either fatal or producing severe neurological deficit, Fields et al., Fisher, and Caplan, in careful investigations on patient survival and outcome following basilar artery occlusion, concluded that more patients than previously presumed survive this event without permanent deficit. Therefore, a rapid, noninvasive technique for helping to detect even one subset of patients with vertebral–basilar disease would be helpful; the possible treatment with anticoagulants exerts its largest efficacy within the first weeks after initiation of TIA's due to stenotic lesions. Furthermore, recent developments in local fibrinolysis and balloon catheter transluminal angioplasty showed promising results only in the early application of these techniques.

While the indication for angiography cannot be based on Doppler findings alone (due to the low sensitivity of c-w Doppler sonography in the detection of basilar artery stenoses of below 60% reduction in lumen diameter), a positive finding can focus early arteriography and treatment on patients with distal vertebral and/or basilar artery disease, especially in patients with no unequivocally localizing symptoms.

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