Background and Purpose—The development of intracranial collateral circulation is associated with a lower risk of stroke. A noninvasive technique that can reliably detect the presence of intracranial collaterals would be a valuable factor in the assessment of risk in patients with occlusive cerebrovascular disease. 

Methods—Color velocity imaging quantification was used to measure the blood flow volume of the common carotid and vertebral arteries in 40 patients with carotid occlusive disease. The blood flow volumes in these arteries were correlated with angiographic evidence of collaterals to establish the best cutoffs for detecting intracranial collateral circulation.

Results—A blood flow volume of either ≥370 mL/min in the common carotid artery or ≥120 mL/min in the vertebral artery was indicative of the presence of intracranial collaterals. The sensitivity and specificity for the common carotid artery were 92.3% [95% confidence interval (CI), 62.1 to 99.6] and 92.1% (95% CI, 77.5 to 97.9), respectively. The sensitivity and specificity for the vertebral artery were 75.0% (95% CI, 35.6 to 95.5) and 87.5% (95% CI, 66.5 to 96.7), respectively.

Conclusions—Color velocity imaging quantification offers a noninvasive, accurate method for detecting the presence of intracranial collateral circulation and quantifying its magnitude. This technique would be a useful adjunct in screening or continuous monitoring of patients with severe carotid occlusive disease. (Stroke. 2002;33:1795-1798.)

Key Words: angiography, digital subtraction ■ blood volume ■ carotid arteries ■ collateral circulation ■ ultrasonography

The brain in humans requires ~15% of the cardiac output, ~800 mL/min, to maintain its proper functions despite its proportionately small size (~2%) relative to the rest of the body. Cerebral hemodynamics are likely to be severely affected by proximal carotid occlusive disease, but the presence of intracranial collaterals, especially those in the circle of Willis, lower the risk of hemispheric stroke and transient ischemic attack both in the long term and perioperatively. Hence, a technique that reliably detects the presence of intracranial collaterals could be useful in the prediction of the risk of recurrent stroke or ischemic disease.

The presence of active collaterals can be deduced from individual blood flow volume (BFV) measurements in the cervicocranial arteries by detecting levels higher than might be expected or from relative flow volume ratios. Because the route of collateral pathways may be on the ipsilateral or contralateral side of carotid obstruction, depending on the prevailing pressure gradient in the anastomotic areas, using flow asymmetry to detect the presence of intracranial collaterals may yield erroneous results. Therefore, we were interested in seeing whether it may be possible to establish a discriminatory upper level of flow that could accurately predict the presence of intracranial collateral circulation with the use of color velocity imaging quantification (CVIQ).

Materials and Methods

The BFV of the common carotid arteries (CCAs) and vertebral arteries (VAs) of 40 symptomatic patients (30 men, 10 women) with a mean age of 65.9 years was studied. All had varying degrees of moderate to severe carotid occlusive disease detected in routine carotid duplex studies. The results were compared with cerebral digital subtraction angiography (DSA), which was performed as a preoperative assessment within 3 months of the ultrasound investigation. The radiologist performing the DSA was blinded to the ultrasound findings at the time of investigation. The rationale for considering only the BFV measurements of the CCA and VA (excluding the internal carotid artery [ICA]) was that these vessels contribute maximally to collateral pathways in carotid occlusive disease.

CVIQ was performed for each patient after standard carotid duplex examination. This technique allowed patients to rest at least 10 minutes before blood flow quantification was measured. The whole procedure added ~10 to 15 minutes to the routine examination time. The BFV of each artery was measured with a 7.5-MHz linear probe of the Philips SD800 ultrasound scanner (Philips Ultrasound International, USA). The average of 3 repeated measurements was taken as the BFV of an artery. The presence of intracranial collateral circulation was confirmed by DSA with appropriate selective angiograms available for interpretation. Different cutoff levels for BFV in the CCA and VA that indicated intracranial collateral flow were established on the receiver-operating characteristics curves.

During BFV measurement, a large sample volume was used. It covered the entire lumen of the chosen vessel and ~1 cm of the long...
axis of the vessel. The site chosen was preferably a straight and nontortuous segment at least 2 cm from the bifurcation. The sampling axis was fixed at an angle of 60°, with the vessel segment being interrogated to avoid variability resulting from difference in insonation angles. A 60° angle was used because it is an optimal angle for BFV measurement when the influence of the angle of insonation on both diameter error and velocity error is taken into account.7 Flow quantification was made with at least 5 cardiac cycles on the color M-mode (the Figure).

On selective CCA angiograms, collateral flow was reported in the CCA when there was crossover circulation to the contralateral cerebral hemisphere or an anastomosis was demonstrated between the external carotid artery and the ICA via the ophthalmic artery and the external carotid artery branches. Collateral flow in a vertebral artery was reported when there was (1) anastomosis between the muscular branches of the vertebral artery and the occipital artery, (2) retrograde filling of the anterior circulation via the posterior communicating artery, or (3) filling of the ipsilateral ICA on selective VA arteriograms.

**Results**

The severity of the carotid occlusive disease was confirmed by DSA in all 40 patients (Table 1) according to the North American Symptomatic Carotid Endarterectomy Trial (NASCET) criteria. Two CCA and 5 VA total occlusions were demonstrated on free flush arteriograms. The success and failure rates for both DSA and CVIQ in the CCA and VA are shown in Table 2. CVIQ of BFV failed in 4 CCA high-grade stenoses because significant downstream flow turbulence was present. Selective DSA could be performed in all except 1 CCA, where tortuous iliac arteries prevented successful negotiation of the catheter into the CCA.

CVIQ was not possible in 6 VAs, including 3 VA hypoplasias (ie, VA <2 mm) and 3 stenoses in interforaminal segments. Technical difficulty was more frequent in DSA, with unsuccessful catheterization because of proximal VA tortuosity in 3 vessels, proximal iliac artery tortuosity in 2, VA hypoplasia in 7, and proximal VA stenoses in 20. Finally, correlation of CVIQ with DSA was possible in only 73 CCAs and 43 VAs in these 40 patients. The mean BFV of the 73 CCAs was 316.5 mL/min (range, 61.9 to 744.0 mL/min) and of the 43 VAs was 94.1 mL/min (range, 6.1 to 684.7 mL/min).

Development of intracranial collateral circulation in the circle of Willis was found to be more prevalent in those patients with more severe carotid disease. It was present in 17 of the 29 patients (58.6%) with severe carotid disease (≥70% stenosis or occlusion) and in 3 of the 11 patients (27%) with moderate carotid disease (≥60% stenosis).

A vessel supplying a collateral circulation in addition to its usual territory should have a higher BFV. The best cutoff BFV for detecting intracranial flow in the CCA and VA was established with receiver-operating characteristics curves. It was found that BFV >370 mL/min for CCA or 120 mL/min for VA was highly accurate in detecting intracranial collateral flow. Their sensitivity, specificity, and 95% confidence intervals (CIs) are shown in Table 3.

| Table 1. The 40 Patients With Varying Degrees of Carotid Occlusive Disease Confirmed by Angiography |
|---|---|---|
| Ipsilateral Disease | Contralateral Disease | n |
| CCA occlusion | CCA stenosis ≥70% | 1 |
| CCA occlusion | ICA stenosis <70% | 1 |
| CCA stenosis ≥70% | ICA stenosis <70% | 1 |
| ICA occlusion | ICA stenosis ≥70% | 2 |
| ICA occlusion | ICA stenosis <70% | 8 |
| ICA stenosis ≥70% | ICA stenosis ≥70% | 4 |
| ICA stenosis <70% | ICA stenosis <70% | 12 |
| ICA stenosis <70% | ICA stenosis <70% | 11 |

| Table 2. Success and Failure Rates of CVIQ and DSA in the CCA and VA of the 40 Patients |
|---|---|---|
| Success | CCA, n (%) | VA, n (%) |
| CVIQ | 74 (95) | 69 (92) |
| DSA | 77 (98.7) | 43 (57.3) |
| Failure | CCA, n (%) | VA, n (%) |
| CVIQ | 4 (5.1) | 6 (8.0) |
| DSA | 1 (1.3) | 32 (42.7) |
Discussion

The development of intracranial collateral circulation is a vital protective mechanism against cerebral ischemia. This was underlined in this study because the presence of intracranial collateral flow was found to be more prevalent in more severe occlusive carotid disease. This is in agreement with the NASCET group study in which the presence of collaterals supplying the symptomatic ICA was found to increase with the severity of stenosis.5

Cerebral angiography, despite its high accuracy in collateral detection, is an invasive procedure with a small but definite hazard of 0.4% neurological complications, even in experienced hands.8 Selective angiography is still considered the gold standard for diagnosing intracranial collateralization by noting the contrast filling in the communicating arteries or the ophthalmic arteries during carotid or vertebral injection.9 The success of the procedures depends largely on the status of the proximal segments of the selected arteries. Stenoses at the origins of the VAs are the major cause of failure in the assessment of collaterals in the posterior circulation. There were 3 VAs that showed evidence of high collateral flow by CVIQ, but confirmation by selective DSA was not available as a result of technical failure. It indicates that CVIQ in the VA is even more sensitive than DSA. In addition, DSA can only detect the presence of a collateral pathway but cannot quantify the BFV it contributes.

Current noninvasive methods for studying intracranial collateral flow are transcranial Doppler ultrasonography,10 transcranial color-coded duplex sonography,11 and MR angiography (MRA).12,13 Transcranial ultrasound techniques (transcranial Doppler ultrasonography and transcranial color-coded duplex sonography) are well known to suffer significant failure as a result of an impenetrable temporal acoustic window.14–16 Despite the reported high accuracy of these techniques in the detection of intracranial collaterals, the successful application can be as low as 30%,16,17 giving a major limitation in the usefulness of these techniques. Although recent advances in the use of intravascular echo-contrast agents in transcranial color-coded duplex sonography can greatly enhance the depiction of basal cerebral circulation,18,19 the echo-contrast agents are relatively expensive and are not easily available in many countries. In addition, this technique adds the necessity of invasiveness and requires prior preparation of the contrast agent ready for use.

MRA is a noninvasive technique that can detect the presence of collateral circulation in the circle of Willis and quantify volume flow rate of intracranial collaterals. However, MRA is still relatively expensive and not freely available and thus is not ideal for screening at regular follow-up. Furthermore, different imaging protocols can be used in MRA to detect collateral circulation in the circle of Willis with varying accuracy.3,20,21 Sensitivity in anterior circulation varies from 89.2% to 95% and that in the posterior circulation from 81.3% to 97%.12,13,22

In severe occlusive carotid disease, the accuracy of CVIQ in detecting intracranial collateral flow in this study is comparable to the above techniques, especially in anterior circulation (Table 4). Comparison of moderate disease with these techniques was not possible because previous studies were performed in severe carotid disease only.

Similar to the other techniques, CVIQ is less accurate in detecting collateral flow in the posterior cerebral circulation compared with the anterior circulation. A high VA BFV is not always associated with intracranial collateral flow. It can be due to a compensatory increase in BFV in 1 VA caused by the presence of stenosis, occlusion, or hypoplasia in the opposite artery, thus lowering the overall accuracy of CVIQ in detecting intracranial collateral flow in the posterior circulation. We have not been able to derive a method that would allow interpretation of this variable.

It is noteworthy that increased BFV in the CCA or VA may be present in patients with intracranial arteriovenous malformation or fistula23 apart from intracranial collateralization secondary to occlusive carotid disease. Because of the possible presence of this kind of vascular lesions, the results of the CVIQ that may suggest intracranial collateralization can be correctly interpreted only if these lesions are excluded by appropriate imaging techniques such as CT or MRI.

The CVIQ technique described in this study has been proved consistent and reliable for BFV measurement in previous studies.24,25 It has been validated against a flow simulator with physiological carotid blood flow, and the flow values obtained were consistent with those of the flow stimulator. Furthermore, the interobserver and intraobserver variabilities were also insignificant. However, one must be aware that BFV measurement will be accurate only if a standardized technique is used and the patient condition is adequate. The measurement may become unreliable in segments with multiple sites of stenoses, in tortuous segments with unpredictable flow velocity vectors and unfavor-
able angle correction, in arteries with poor color signals resulting from attenuating subcutaneous fat, or in patients with great respiratory vessel movement.

This study opted to use the CVIQ technique instead of the more popular Doppler technique to measure BFV because it has been shown that CVIQ is more accurate than spectral Doppler technique in the determination of BFV in the carotid arteries, where the BFV is significantly overestimated by spectral Doppler technique.24

In conclusion, CVIQ offers a quick, noninvasive, accurate method for the detection of intracranial collateral flow by measuring the cervicocranial arterial BFV. This technique not only is less technically difficult than angiography and MRA, especially in posterior circulation, but also is more successfully applicable than transcranial Doppler ultrasonography or transcranial color-coded duplex sonography. Another advantage of CVIQ is the ability to quantify collateral BFV, which is potentially a reflection of the adequacy of the collateral circulation. Therefore, this technique is ideal for screening and continuous monitoring of patients with severe carotid occlusive disease and assessing their hemodynamic status.

References
Color Velocity Imaging Quantification in the Detection of Intracranial Collateral Flow
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