Noninvasive Assessment of Cerebral Collateral Blood Supply Through the Ophthalmic Artery

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We assessed the potential of 2-MHz pulsed-wave transorbital Doppler ultrasonography to delineate the role of the ophthalmic artery as a source of collateral cerebral blood supply by comparing oculopneumoplethysmography, transorbital Doppler ultrasonography, periorbital continuous-wave Doppler ultrasonography, and transcranial Doppler ultrasonography in 25 patients with unilateral internal carotid artery occlusion and five controls with 10 normal internal carotid arteries. Systolic ophthalmic artery blood velocity was reduced ipsilateral to an internal carotid artery occlusion (38.2 ± 10.2 cm/sec) compared with the contralateral and control velocities (46.0 ± 10.3 and 47.5 ± 6.8 cm/sec, respectively; p < 0.05). Ophthalmic systolic pressure measured by oculopneumoplethysmography was 94.7 ± 13.2 mm Hg ipsilateral to an internal carotid artery occlusion compared with 108.4 ± 15.3 mm Hg on the contralateral side (p < 0.01). Transorbital and periorbital Doppler ultrasonography detected reversed ophthalmic artery blood flow ipsilateral to an internal carotid artery occlusion in 44.0% and 40.0% of the patients, respectively. Systolic middle cerebral artery blood velocity was 55.2 ± 22.3 cm/sec ipsilateral to an internal carotid artery occlusion in 44.0% and 40.0% of the patients, respectively. Systolic middle cerebral artery blood velocity was 55.2 ± 22.3 cm/sec ipsilateral to an internal carotid artery occlusion compared with 79.4 ± 23.5 cm/sec on the contralateral side (p < 0.05) and 101.2 ± 18.9 cm/sec in the controls (p < 0.05). Reversed ophthalmic artery blood flow was associated with a low middle cerebral artery blood velocity and the lack of major intracerebral collaterals. Transorbital Doppler ultrasonography permits noninvasive evaluation of the ophthalmic artery. Transorbital Doppler measurements correlate with those from oculopneumoplethysmography and transcranial Doppler ultrasonography, reflect the hemodynamic consequences of internal carotid artery occlusion, and demonstrate the importance of the ophthalmic artery as a source of collateral blood supply to the brain.

The hemodynamic sequelae of extracranial cerebrovascular disease can be assessed through the orbit using oculopneumoplethysmography (OPG). Recently developed for insonation of the cerebral vasculature through a transtemporal approach, 2-MHz pulsed-wave transcranial Doppler ultrasonography (TCD) can also be employed through a transorbital approach for direct, noninvasive evaluation of the ophthalmic artery and carotid siphon. Pulsed-wave transorbital Doppler ultrasonography has been used to identify carotid siphon stenoses, but its potential in investigation of the ophthalmic artery has not been fully evaluated. The purposes of this study are 1) to examine the potential of transorbital Doppler ultrasonography in both the quantitative and the qualitative assessment of blood flow in the ophthalmic artery, 2) to delineate the relation between ophthalmic artery blood velocity as determined by transorbital Doppler ultrasonography and ophthalmic systolic pressure as measured by OPG, 3) to examine the role of the ophthalmic artery as a circuit for collateral blood supply from the extracranial to the intracranial cerebral circulations, and 4) to correlate transorbital Doppler ultrasonography and OPG findings with middle cerebral artery (MCA) blood velocity as measured by TCD.

Subjects and Methods

Between June and January 1988 we studied 25 unselected patients referred to the Scripps Clinic Vascular Laboratory with unilateral internal carotid...
artery (ICA) occlusion (mean±SEM 63.7±9.6 years). Five healthy volunteers (10 normal ICAs) served as controls (mean±SEM age 39.2±14.7 years). Patients and controls underwent duplex scanning of the extracranial carotid vessels, periorbital continuous-wave Doppler examination, TCD, transorbital Doppler evaluation, and OPG.

Duplex scanning of the extracranial arteries was performed, and severity of the ICA occlusive lesions was assessed. Periorbital Doppler examination was performed using a 5-MHz probe, and ophthalmic artery blood flow was classified as forward or reversed. The TCD study was then performed using a 2-MHz, range-gated, pulsed-wave Doppler device (TC 2-64, Carolina Medical Electronics, Inc., King, N.C., or Transpect, Medasonics, Mountainview, Calif.). The standard TCD evaluation, including the identification of collaterals, has been reported in detail.4-5 Those transorbital Doppler evaluation was performed using the same equipment. With the patient in the same position, the 2-MHz probe was placed over the orbit using coupling gel, with the eyelid closed. The Doppler power was reduced to 10% of that required to penetrate the bony skull through the temporal portion. The patient was instructed to turn the eyes toward the contralateral side to remove the refractive power of the ocular lenses. The probe was applied without pressure in the anterior-posterior direction. The ophthalmic artery was insonated at a depth of 30–60 mm (Figure 1) and tracked along its course; the optimal signal was usually obtained at 35–40 mm. Blood flow in the ophthalmic artery was usually toward the probe (upwardly deflected waves) but was occasionally reversed (downward deflection). The angle of insonation was <15°, and the normal ophthalmic artery signal demonstrated a slightly resistive pattern.

For each MCA, ophthalmic artery, and carotid siphon Doppler signal the peak systolic, mean, and end-diastolic velocities (Vs) were recorded and the pulsatility index was calculated as$$(V_{sys}-V_{dia})/V_{mean}$$.

We used OPG-Gee to evaluate ophthalmic artery pressure because this technique has demonstrated accuracy either superior or comparable to that of other available methods.2,8 The OPG-Gee apparatus was provided by Electro-Diagnostic Instruments, Burbank, Calif. Following a several-minute resting period, bilateral upper extremity blood pressures were obtained, anesthetic ophthalmic drops were placed bilaterally, and the OPG-Gee examination was performed in the routine manner. The patient remained in the supine position, the plastic OPG ocular cups were placed lateral to the cornea on each side, and vacuum suction (300 mm Hg for normotensive patients and 500 mm Hg for hypertensive patients) was applied. Simultaneous electrocardiogram recording was performed. Two measurements of ocular systolic pressure were taken in each patient, and the higher reading was used for evaluation. After the OPG study, the brachial systolic pressure was measured in the upper extremity. Standardized definitions were used to interpret the results.2,9 A ratio of ophthalmic systolic pressure to brachial systolic pressure that was ≥1 mm below a regression line defined by the formula ophthalmic systolic pressure = 39.0 + 0.43 × brachial systolic pressure was considered abnormal.

Arterial blood velocities and pulsatility indexes ipsilateral to ICA occlusions were compared with those from the contralateral patent sides and the controls using Student's two-tailed t test. The same test was used to compare patients with different collateral patterns. Ophthalmic systolic pressure as a function of ophthalmic artery blood velocity was
evaluated using linear regression analysis. Statistical analysis was performed using the CLINFO PLUS program (provided by the Division of Research Resources, National Institutes of Health, Bethesda, Md.). Results are given as mean±SEM.

Results

Systolic MCA blood velocity was decreased ipsilateral to an ICA occlusion (55.2±22.3 cm/sec) compared with that in the contralateral patent artery (79.4±23.5 cm/sec, p<0.05) and the normal controls (101.2±18.9 cm/sec, p<0.05). The MCA pulsatility index was 0.69±0.23 ipsilateral to an ICA occlusion compared with 1.02±0.17 on the contralateral side and 1.05±0.07 in the controls (p<0.05). Ophthalmic systolic pressure varied directly with the brachial systolic pressure in the controls (r=0.924, p<0.01; Figure 2A). There was also a direct relation between ophthalmic systolic pressure and brachial systolic pressure both contralateral and ipsilateral to an ICA occlusion (Figures 2B and 2C, respectively). Ophthalmic systolic pressure was 94.7±13.2 mm Hg ipsilateral to an ICA occlusion and 108.4±15.3 mm Hg on the contralateral patent side in the same patient (p<0.01).

Systolic ophthalmic artery blood velocity was reduced distal to an ICA occlusion (38.2±10.2 cm/sec) compared with the contralateral and control veloci-

**Figure 2. Scatter plots of correlation between ophthalmic systolic pressure and brachial systolic pressure in normal controls (A) and in patients contralateral (B) and ipsilateral (C) to internal carotid artery occlusion. Most ophthalmic-to-brachial systolic pressure ratios (OPG) values ipsilateral to occlusion were abnormal. Reversed ophthalmic artery (OA) blood flow is represented by closed circles.**
Systolic ophthalmic artery blood velocity varied directly with ophthalmic systolic pressure in the controls \( r=0.765, p<0.01; \) Figure 3A and in the patients contralateral to the ICA occlusion \( r=0.402, p=0.051; \) Figure 3B. However, ipsilateral to an ICA occlusion the relation between ophthalmic artery blood velocity and ophthalmic systolic pressure varied depending upon the direction of ophthalmic artery blood flow (Figure 4).

Intracranial collateral patterns were delineated in 22 patients using TCD; the remaining three patients could not be adequately evaluated due to technical difficulties. Differences in MCA blood velocity, ophthalmic systolic pressure, and the percentage with reversed ophthalmic artery blood flow for patients with various collateral patterns are summarized in Table 1. All 22 patients had some identifiable cerebral collateral pathway: an anterior communicating artery, a posterior communicating artery, an external carotid artery collateral, or some combination of these. The MCA blood velocity ipsilateral to an ICA occlusion was not affected by the presence of an anterior communicating artery or an external carotid artery collateral, but it was significantly higher when an ipsilateral posterior communicating artery was demonstrated \( p<0.05 \). Reversed blood flow in the ophthalmic artery occurred in all patients without major intracerebral collaterals \( n=4 \).

**Discussion**

The TCD measurements of MCA blood velocity through a transtemporal approach have previously been used in the assessment of the cerebral hemodynamic consequences of extracranial arterial occlusive

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**Figure 3.** Scatter plots of correlation between ophthalmic systolic pressure and ophthalmic artery blood velocity in normal controls (A) and in patients contralateral to internal carotid artery occlusion (B).

**Figure 4.** Scatter plots of relation between ophthalmic systolic pressure and ophthalmic artery blood velocity ipsilateral to internal carotid artery occlusion. Reversed blood flow is shown as negative velocity.
The MCA blood velocity correlates with regional cerebral blood flow measurements and has been employed to evaluate cerebral perfusion in patients with temporary clamp occlusion of the carotid artery during endarterectomy and in patients with atherosclerotic ICA occlusion. Decreased blood velocity and pulsatility of the MCA ipsilateral to an ICA occlusion has been demonstrated previously and was confirmed in this study. The TCD technique has also shown promise in the identification of hemodynamically significant intracerebral collaterals. The ophthalmic artery is an accessible brain artery that also reflects hemodynamic alterations due to cerebrovascular disease as demonstrated by OPG. The recent development of transorbital Doppler ultrasonography permits direct evaluation of the ophthalmic artery through the orbit without interference from the bony skull and with minimal error due to the favorable angle between the ophthalmic artery and the Doppler beam (<15°). This provides the opportunity to examine directly the factors that may enhance our understanding of the role of the ophthalmic artery in cerebrovascular disease.

The direct relation between ophthalmic systolic pressure and ophthalmic artery blood velocity present in this study is similar to that between carotid artery stump pressure and MCA blood velocity measured during common carotid artery crossclamping for carotid endarterectomy. Complete understanding of cerebral blood pressure-flow relations may guide the management of patients with compromised cerebral perfusion in the future. In addition, transorbital Doppler insonation of the ophthalmic artery may be useful for continuous intraoperative monitoring in patients who have an inadequate temporal window.

Transorbital Doppler examination detected continuously reversed ophthalmic artery blood flow in a significant percentage of our patients. Reversed flow was observed only ipsilateral to an ICA occlusion or preocclusive stenosis and was associated with reduced ophthalmic systolic pressure and MCA blood velocity on the same side. The ophthalmic artery blood velocity was inversely related to the ophthalmic systolic pressure (Figure 4) in arteries with reversed flow. Ophthalmic artery blood flow was more likely to be reversed when no major intracranial collaterals could be demonstrated (Table 1). These data suggest that the ophthalmic artery plays a significant role as a collateral circuit from the extracranial to the intracranial cerebral circulations. Transorbital Doppler ultrasonography may therefore be useful in selecting patients who might benefit from external carotid endarterectomy and in the management of ophthalmic symptoms of cerebrovascular disease. Delineating the direction and quantifying the velocity of ophthalmic artery blood flow identifies patients with established extracranial-to-intracranial collateral circuits through which cerebral emboli might pass or those in whom blood flow may be improved by reconstructive external carotid artery surgery.

Although there is some controversy regarding the optimal method of screening patients for significant extracranial cerebrovascular disease, OPG has been used at many institutions because of its simplicity and reproducibility. This technique gives an approximation of the level of cerebral perfusion, which is influenced by both arterial occlusive disease of the extracranial and intracranial circulations and the collateralization that has formed to compensate for these lesions. Transorbital Doppler ultrasonography permits a thorough evaluation of the role of the ophthalmic artery and carotid siphon in the pathophysiologic process under investigation but is not

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### Table 1. Effect of Cerebral Collateral Patterns

<table>
<thead>
<tr>
<th>Collateral pattern</th>
<th>n</th>
<th>Middle cerebral artery blood velocity (cm/sec)</th>
<th>Ophthalmic systolic pressure (mm Hg)</th>
<th>Reversed OA blood flow (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACoA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Present</td>
<td>14</td>
<td>51.8±27.3</td>
<td>91.0±13.3</td>
<td>50.0</td>
</tr>
<tr>
<td>Absent</td>
<td>8</td>
<td>60.6±11.8</td>
<td>99.6±14.3</td>
<td>37.5</td>
</tr>
<tr>
<td>Ipsilateral PCoA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Present</td>
<td>16</td>
<td>60.4±24.1</td>
<td>96.5±10.6</td>
<td>40.0</td>
</tr>
<tr>
<td>Absent</td>
<td>6</td>
<td>40.0±7.9*</td>
<td>88.7±20.5</td>
<td>50.0</td>
</tr>
<tr>
<td>ACoA and/or PCoA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Present</td>
<td>18</td>
<td>56.2±23.8</td>
<td>95.2±12.9</td>
<td>42.1</td>
</tr>
<tr>
<td>Absent</td>
<td>4</td>
<td>45.0±7.1</td>
<td>85.5±27.6</td>
<td>100.0</td>
</tr>
<tr>
<td>External to internal circulation through OA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Present</td>
<td>11</td>
<td>50.1±30.7</td>
<td>84.9±14.5</td>
<td>100.0</td>
</tr>
<tr>
<td>Absent</td>
<td>14</td>
<td>59.9±16.7</td>
<td>100.2±8.0*</td>
<td>0</td>
</tr>
</tbody>
</table>

OA, ophthalmic artery; ACoA, anterior communicating artery; PCoA, posterior communicating artery. Data are mean±SEM or percentage. Full delineation of intracranial collateral patterns was achieved by transcranial Doppler ultrasonography in 22 of 25 patients.

*p<0.05 different from present by Student's two-tailed t test.
appropriate for screening purposes because it is time-consuming and there is some variability in velocity measurements.

Direct, noninvasive evaluation of the ophthalmic artery can be performed using transorbital Doppler ultrasonography. The direction and velocity of ophthalmic artery blood flow as determined by this technique correlate with those determined by OPG and TCD, reflect the presence of ICA occlusion, and demonstrate the importance of the ophthalmic artery as a source of collateral blood supply to the brain. Future studies with transorbital Doppler ultrasonography may help to delineate the role of the ophthalmic artery in the pathophysiology of cerebrovascular disease and its subsequent assessment and clinical management.

References

KEY WORDS • collateral circulation • ophthalmic artery • ultrasonics
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doi: 10.1161/01.STR.22.1.31

*Stroke* is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0039-2499. Online ISSN: 1524-4628

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