Estimation of Cerebral Blood Flow Through Color Duplex Sonography of the Carotid and Vertebral Arteries in Healthy Adults

Martin Schöning, MD; Jochen Walter; Peter Scheel, MD

Background and Purpose To noninvasively estimate cerebral blood flow volume, a prospective study of color duplex sonography of the common, external, and internal carotid arteries and vertebral arteries of healthy adults was done. Cerebral blood flow was calculated with the sum of flow volumes in the internal carotid and vertebral arteries of both sides.

Methods Using a 7.0-MHz linear transducer of a computed sonography system, cervical arteries of 48 volunteers (23 women, 25 men; mean age, 35 ±12 years) were examined. We measured angle-corrected time-averaged velocities and the diameter of the vessels and calculated the flow volumes of all arteries. In addition, peak systolic, maximum end-diastolic, and time-averaged maximum velocities and the resistance, pulsatility, and spectral broadening indexes were determined. Furthermore, we analyzed the side-to-side difference, age dependence, and long-term reproducibility of these parameters.

Results The mean±SD values of flow volumes in the common, internal, and external carotid and vertebral arteries were 470±120, 265±62, 160±66, and 85±33 mL/min on either side, respectively. Total cerebral blood flow was 701±104 mL/min (corresponding to 54±8 mL/100 g per minute), with no variation in age or sex. Long-term reproducibility of cerebral blood flow and flow volumes in all vessels was significant (P<.01).

Conclusions We conclude that color duplex sonography of cervical arteries is potentially a practical method for estimating total cerebral blood flow. This noninvasive technique may be ideally suited for bedside and follow-up examinations of the critically ill patient. In future studies it should be compared with established radionuclide techniques. (Stroke. 1994;25:17-22.)

Key Words • carotid arteries • cerebral blood flow • ultrasonics • vertebral artery

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Mean ± SD values and ranges of the angle of insonation, all flow velocities and waveform parameters, the diameter of the vessels, and the calculated flow volumes are shown in Table 1. The CCA vessel wall showed a marked expansion during a cardiac cycle of 0.8

[Table 1. Normal Values for Flow Velocities, Waveform Parameters, Vessel Diameters, and Flow Volumes in Carotid and Vertebral Arteries]

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Angle, °</th>
<th>Vs, cm/s</th>
<th>Ved, cm/s</th>
<th>TAV, cm/s</th>
<th>TAMX, cm/s</th>
<th>RI</th>
<th>PI</th>
<th>SBI'</th>
<th>d, mm</th>
<th>Flow Vol, mL/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCA</td>
<td>65±4</td>
<td>96±25</td>
<td>26±6</td>
<td>25.4±5.4</td>
<td>40.9±8.0</td>
<td>0.72±0.07</td>
<td>1.72±0.50</td>
<td>0.38±0.06</td>
<td>6.3±0.9</td>
<td>470±120</td>
</tr>
<tr>
<td></td>
<td>(54-71)</td>
<td>(50-169)</td>
<td>(10-37)</td>
<td>(15-65)</td>
<td>(0.55-0.90)</td>
<td>(0.91-3.33)</td>
<td>(0.22-0.54)</td>
<td>(4.7-9.7)</td>
<td>(267-779)</td>
<td></td>
</tr>
<tr>
<td>ICA</td>
<td>58±6</td>
<td>66±16</td>
<td>26±6</td>
<td>24.9±5.2</td>
<td>37.5±7.7</td>
<td>0.60±0.07</td>
<td>1.08±0.29</td>
<td>0.33±0.06</td>
<td>4.8±0.7</td>
<td>265±62</td>
</tr>
<tr>
<td></td>
<td>(45-71)</td>
<td>(36-115)</td>
<td>(10-40)</td>
<td>(11-38)</td>
<td>(0.44-0.80)</td>
<td>(0.47-2.09)</td>
<td>(0.19-0.55)</td>
<td>(3.3-7.2)</td>
<td>(154-493)</td>
<td></td>
</tr>
<tr>
<td>ECA</td>
<td>59±7</td>
<td>83±17</td>
<td>17±5</td>
<td>19.6±4.1</td>
<td>30.7±6.6</td>
<td>0.79±0.05</td>
<td>2.17±0.51</td>
<td>0.36±0.09</td>
<td>4.1±0.6</td>
<td>160±66</td>
</tr>
<tr>
<td></td>
<td>(40-75)</td>
<td>(45-136)</td>
<td>(9-28)</td>
<td>(11-31)</td>
<td>(0.65-0.90)</td>
<td>(1.30-3.46)</td>
<td>(0.17-0.55)</td>
<td>(2.8-6.0)</td>
<td>(55-474)</td>
<td></td>
</tr>
<tr>
<td>VA</td>
<td>62±6</td>
<td>48±10</td>
<td>16±4</td>
<td>15.6±3.6</td>
<td>24.3±5.2</td>
<td>0.66±0.07</td>
<td>1.35±0.40</td>
<td>0.35±0.11</td>
<td>3.4±0.6</td>
<td>85±33</td>
</tr>
<tr>
<td></td>
<td>(40-72)</td>
<td>(28-71)</td>
<td>(8-26)</td>
<td>(9-26)</td>
<td>(0.52-0.83)</td>
<td>(0.60-2.56)</td>
<td>(0.02-0.61)</td>
<td>(1.8-4.5)</td>
<td>(21-165)</td>
<td></td>
</tr>
</tbody>
</table>

All parameters are mean ± SD, with range in parentheses. Angle indicates angle of course of vessel to Doppler beam; Vs, peak systolic velocity; Ved, maximum end-diastolic velocity; TAV, time-averaged velocity; TAMX, time-averaged maximum velocity; RI, resistance index [(Vs-Ved)/Vs]; PI, pulsatility index [(Vs-Ved)/TAMX]; SBI', modified spectral broadening index (1 -TAV/TAMX); d, diameter of the vessel; Flow Vol, flow volume; CCA, common carotid artery; ICA, internal carotid artery; ECA, external carotid artery; and VA, vertebral artery.

In the color Doppler mode, the velocity range of the color scale was set slightly higher than the Nyquist limit to enable easy detection of flow disturbances. Pulsed Doppler measurement was done using a sample volume covering the entire luminal width. Flow velocities were recorded only if the signal was stable for at least 5 seconds. Exact angle correction of Doppler frequencies was achieved by adjusting the angle between the Doppler beam and the course of the vessel (along the walls of the vessel as well as along the color Doppler stream). In our opinion, in this way it is possible to estimate the angle of insonation with an accuracy of ±1 to 2 degrees. All duplex measurements were documented using a video printer.

In examining the VA, the transducer was positioned along the CCA, shifted laterally, and angled until the intertransverse segment of the VA was seen. The luminal width was measured mainly at the C4-C5 intertransverse area, using the magnified B-mode image. Duplex measurements were recorded as described above.

The following measurements of angle-corrected flow velocities were taken in each artery: (1) peak systolic velocity (Vs); (2) maximum end-diastolic velocity (Ved); (3) time-averaged velocity (TAV), ie, the mean of all frequencies occurring above and below the baseline over at least three complete pulses; and (4) time-averaged maximum velocity (TAMX), ie, the averaged mean of peak flow velocities over a complete cardiac cycle. We calculated the resistance index (RI) according to Pourcelot14 as RI = (Vs-Ved)/Vs, and the pulsatility index (PI) according to Gosling and King15 as PI = (Vs-Ved)/TAMX. In addition, the modified spectral broadening index (SBI')14,15 SBI' = 1 - TAV/TAMX, was calculated.

The flow volume (Q) of each artery was determined using the formula Q = TAV × A. The area (A) of circular vessels can be calculated with the diameter (d) as [(d/2)^2] × PI. Flow volumes in the CCA were determined with the minimum diameter of the M-mode registration. The sum of the ICA and ECA flow volumes was compared with that of the CCA on each side. CBF was calculated as the sum of the flow volumes of ICA and VA of both sides.

In a reproducibility study, flow velocity and flow volume measurements in all cervical arteries were repeated approximately 1 year (range, 10 to 19 months) after the first session in 22 volunteers of the same group (9 women, 13 men; mean ± SD age, 33±12 years) by the same examiner. The duration of rest before the examination began was 5 to 10 minutes. The examination procedure was identical to that described above.

Statistical analysis was done with the SAS program. All parameters and side-to-side differences are indicated as mean ± SD. Age dependence of flow velocities and flow volumes was tested by calculating Spearman's correlation coefficient. The Pearson correlation coefficient was used in the reproducibility study. The level for statistical significance was set at P≤0.01 for all parameters.

Results

In 46 volunteers, all cervical arteries could be examined by color duplex sonography. In two subjects, duplex measurements were incomplete because the carotid bulb on one side was situated high in the neck (data on one ICA and two ECA are missing). In all cases, the carotid bulb proved to be normal in B-mode scan and color Doppler mode.

Mean ± SD values and ranges of the angle of insonation, all flow velocities and waveform parameters, the diameter of the vessels, and the calculated flow volumes are shown in Table 1. The CCA vessel wall showed a marked expansion during a cardiac cycle of 0.8
TABLE 3. Age Dependence of Flow Velocities, Waveform Parameters, Vessel Diameters, and Flow Volumes

<table>
<thead>
<tr>
<th>Vessel</th>
<th>n</th>
<th>Vs, cm/s</th>
<th>TAV, cm/s</th>
<th>TAMX, cm/s</th>
<th>TAV, cm/s</th>
<th>d, mm</th>
<th>Flow Vol, mL/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCA</td>
<td>48</td>
<td>6.9±16.2</td>
<td>1.9±6.8</td>
<td>1.8±3.9</td>
<td>0.3±0.6</td>
<td>10±104</td>
<td></td>
</tr>
<tr>
<td>ICA</td>
<td>47</td>
<td>1.3±16.1</td>
<td>0.5±7.7</td>
<td>0.4±4.8</td>
<td>0.1±0.7</td>
<td>9±77</td>
<td></td>
</tr>
<tr>
<td>ECA</td>
<td>46</td>
<td>0.7±17.2</td>
<td>1.4±7.6</td>
<td>1.0±5.4</td>
<td>0.1±0.5</td>
<td>4±66</td>
<td></td>
</tr>
<tr>
<td>VA</td>
<td>48</td>
<td>3.1±12.0</td>
<td>3.2±6.9</td>
<td>1.2±4.7</td>
<td>0.2±0.7</td>
<td>18±48</td>
<td></td>
</tr>
</tbody>
</table>

All parameters are mean±SD. n indicates number of paired vessels investigated; Vs, peak systolic velocity; TAMX, time-averaged maximum velocity; TAV, time-averaged velocity; d, diameter of the vessel; Flow Vol, flow volume; CCA, common carotid artery; ICA, internal carotid artery; ECA, external carotid artery; and VA, vertebral artery.

*P<.01.

In the reproducibility study, there were no significant differences between the test and retest examination of Vs, Ved, TAMX, and the waveform parameters (RI, PI, and SBI'). The Pearson correlation coefficient between both series was high for the PI in the VA (.63), CCA (.61; P=.0001), and ICA (0.47; P<.001) but low in the ECA (.29; P>.01).

Mean TAV data were almost identical in both series, but the correlation was poor (Table 4). In contrast, diameter measurements correlated significantly in all vessels, although there were minimal but significant differences in VA and ECA diameter between the first and second series. Apart from insignificant differences in the flow volumes of all arteries, the test and retest results correlated well with each other. Calculated mean total CBF was lower in the reproducibility study (P<.01), but the correlation between both series was also significant (Fig 3).

Discussion

Despite numerous publications dealing with color duplex examination of the carotid arteries and VA, few reference values exist for this method. In this article we have established a complete set of normal data on various flow velocities and waveform parameters for all cervical arteries, including analysis of side-to-side differences, correlation with aging, and long-term reproducibility. For reasons of brevity, we cannot compare all these results with those of other studies. Therefore, we prefer to concentrate on data relevant to flow volume estimation.

The TAV we calculated in the CCA of healthy adults are similar to those reported by Donis et al. Normal data on TAV in ICA, ECA, and VA do not exist, as far as we know. Diameters of the extracerebral carotid arteries and VA have been described by other
groups; they compared well16,20 with our measurement or were slightly higher.17-19

In some of our cases, the VA were found to be asymmetrical, with the dominant artery situated more often on the left side—an observation that has been reported earlier.19,20 Because the definition of VA hypoplasia is still arbitrary, differences in the rate of hypoplasia ranging from 2% to 9% have been reported.19,21 According to our results, hypoplasia could be defined either with the parameter of diameter or, instead, the flow volume: eg, a diameter lower than 2.2 mm or a flow volume of less than 30 mL/min would result in a rate of hypoplasia of 5% and 3%, respectively.

In regard to the estimation of CBF through Doppler or duplex techniques, in most published studies4-8,22-24 the CCA has been investigated because it is easily accessible for examination. In our study, this vessel posed the most difficulties in the proper evaluation of CBF because relatively high angle correction was necessary, marked variation of the vessel diameter occurred during a cardiac cycle, and there was the lowest reproducibility of flow volume measurements of all arteries examined. Moreover, an age-related rise in CCA blood volume corresponded to an increase in the amount of blood directed into the ECA and not of that to the brain. On the contrary, in ICA and VA the mean angle of insonation was lower, the expansion of the vessel wall minimal, and the reproducibility of flow volume estimate significant.

There is an "internal standard" for testing the reliability of flow volume measurements in man, namely, the sum of flow volumes passing through the ICA and ECA should mathematically correspond to the CCA flow volume. In this study, the mean of CCA flow volumes exceeded the sum of ICA and ECA flow volumes to a low extent (10%), although significantly, but their correlation was also significant. In a recent report by Juul et al,25 the sum of ICA and ECA flow volumes correlated well with measurements in the CCA, but CCA flow volumes also appeared to be slightly higher (mean data of flow volumes were not indicated). For the reasons cited above, CCA flow volume measurements seem to be less reliable than those of the ICA, and therefore should no longer be considered representative for CBF volume.

In the reproducibility part of our study, insignificant mean differences in ICA and VA flow volume measurements accounted for a significant difference in CBF estimation (mean difference, 8%), but again a significant correlation existed (Table 4, Fig 3). It is a well-known fact that flow volume measurements performed using the duplex scan technique are vulnerable to minor errors.26-28 The following were related to the respective mean values of the ICA in our study: errors of 1 degree in angle determination, of 0.1 mm in diameter, and of 1 cm/s in TAV measurements result in a 3%, 4%, and 4% deviation of flow volume estimation, respectively. If more than one of these minimal errors occur, they can easily add up to a 10% deviation in flow volume measurement. In fact, the significant difference in the

![Fig 2. Scatterplot shows cerebral blood flow (CBF) measurements related to age in 47 subjects.](image)

![Fig 3. Scatterplot shows reproducibility of cerebral blood flow (CBF) measurements in 22 subjects.](image)

**Table 4. Reproducibility of Time-Averaged Velocity, Vessel Diameter, and Flow Volume Measurements of Carotid and Vertebral Arteries in 22 Subjects**

<table>
<thead>
<tr>
<th>Time-Averaged Velocity</th>
<th>Diameter</th>
<th>Flow Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Difference, cm/s</strong></td>
<td><strong>Correlation Coefficient</strong></td>
<td><strong>Difference, mm</strong></td>
</tr>
<tr>
<td>CCA -1.0±6.3</td>
<td>.32</td>
<td>0.2±0.6</td>
</tr>
<tr>
<td>ICA -0.1±6.2</td>
<td>.25</td>
<td>0.1±0.7</td>
</tr>
<tr>
<td>ECA -0.6±6.3</td>
<td>.19</td>
<td>0.4±0.5†</td>
</tr>
<tr>
<td>VA 0.0±4.5</td>
<td>.27</td>
<td>0.2±0.4*</td>
</tr>
</tbody>
</table>

Difference between test and retest measurement (mean±SD) and the Pearson correlation coefficient of both measurements are indicated. CCA indicates common carotid artery; ICA, internal carotid artery; ECA, external carotid artery; and VA, vertebral artery.

*P<.001; †P<.0001; ‡P<.005.
estimation of CBF in our reproducibility study was a result of minimal (0.1 to 0.2 mm) mean deviations of ICA and VA diameter measurements, while the mean of TAV data was almost identical in both series. Some difference in long-term reproducibility of CBF might be explained by different states of mental activity, e.g., because the period of rest before the CBF measurement was shorter in the restest or because the volunteers may have become accustomed to the test situation. Same-day, day-to-day, and intraobserver and interobserver reliabilities of color duplex CBF measurements were not part of this preliminary investigation; this has to be performed carefully in a separate study.

The flow volume estimations we made of the CCA compared well with those reported in various studies5,6,8 with the exception that they tended to decrease with age. In the study done by Leopold et al,9 mean ± SD flow volumes in the ICA of healthy adults were 254 ± 56 mL/min, thus finding a parallel in our results. Mean flow volumes (during normocapnia and normoxia) reported by Fortune et al,10 however, were higher (330 mL/min) and possibly due to the fact that their ICA flow volumes (plus VA flow volumes of approximately 170 mL/min) would amount to a rather high mean CBF of 830 mL/min. Bendick and Glover29 determined VA flow volumes in patients with asymptomatic bruits but did not provide mean data for this group.

Total CBF has, until now, not been determined by duplex measurements. During the last 40 years, CBF has been measured by many groups using various methods: in 1948, Kety and Schmidt10 proposed normal data on CBF with a mean of 54 mL/100 g per minute by using the nitrous oxide method; more than 40 years later, Waldemar et al11 reported a 54 ± 9 mL/100 g per minute (mean ± SD) CBF with the 133Xe inhalation technique and SPECT. Similar data (56 ± 7 mL/min) were obtained by the group of Shirahata.32 By assuming a mean brain weight33 of 1300 g, our data would correspond to 54 ± 8 mL/100 g per minute, thus correlating well with nitrous oxide and SPECT measurements. In future studies, the color Doppler method should be compared with the SPECT or PET technique in one subject group.

The question of whether there is a decline in global CBF with progressive age has not yet been clearly resolved. Some study groups34-37 have claimed that a decline occurs. Our findings reflect those of other groups, which could not establish any change in CBF due to aging.31,38

In conclusion, we think that color duplex sonography of cervical arteries is potentially a practical technique for estimating total CBF, provided that all criteria for correct measurement are fulfilled. With some practice, flow volume measurements of both ICA and VA can be done in 10 to 15 minutes. This method may be suitable for bedside monitoring of CBF in the critically ill patient, in conditions of low perfusion in the brain such as brain edema and severe subarachnoid hemorrhage, or in conditions of low cerebral perfusion such as infratentorial and supratentorial or dural arteriovenous malformations, as well as in ICA stenoses with marked collateralization via the ECA. The normal data provided in this and previous studies12,13,39 should aid the process of defining normal and abnormal flow patterns in extracerebral and intracerebral arteries.

Acknowledgment

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References


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