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

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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.

Ever since Kety and Schmidt first measured cerebral blood flow (CBF) by using nitrous oxide, various other techniques have been described. The 133Xe inhalation technique and single-photon emission computed tomography (SPECT) and positron emission tomography (PET) are the techniques currently used in quantifying total and regional CBF for clinical and scientific purposes. However, these methods cannot be used for bedside examination and in follow-up controls, eg, in the critically ill patient.

Ultrasound and Doppler methods are ideally suited for bedside examinations. Reports have described the use of Doppler and duplex techniques in estimating CBF by measuring flow volumes of the common carotid artery (CCA) and the internal carotid artery (ICA) in healthy adults. Total CBF estimation through quantitative Doppler flow volume measurement of the extracranial ICA and vertebral arteries (VA) had already been proposed by Furuhata et al, but normal data are still unavailable.

Therefore, we conducted a prospective study of color duplex examinations of the CCA, ICA, and external carotid arteries (ECA) and the VA in healthy adults. Our aim was to obtain normal data on flow velocities and waveform parameters and to calculate the flow volumes in these vessels, as well as to analyze the normal side-to-side difference, age dependence, and long-term reproducibility of these parameters. CBF volume was to be estimated by adding the flow volumes of the ICA and VA together.

Subjects and Methods

Using color duplex sonography of the entire extracranial carotid system and the VA, we examined 48 healthy volunteers (23 women, 25 men) who had no medical history or physical signs of cerebrovascular disease. Mean age was 35±12 years (range, 20 to 63 years). A 7.0-MHz linear array transducer of a computed sonography system (Acuson 128, Mountain View, Calif) was used.

Transcranial color duplex examination of the basal cerebral arteries was performed before the extracranial arteries were viewed. The volunteers, therefore, lay supine for at least 30 minutes before the cervical arteries were examined.

The CCA, ICA, and ECA were examined with the head slightly tilted upward, in midline position. The site of measurement was approximately 1.5 cm below the carotid bulb in the CCA and 1.0 to 1.5 cm away from the bifurcation in ICA and ECA. The B-mode image was magnified to achieve a higher resolution of detail. The luminal diameter of the vessels could thus be measured optimally.

Because the CCA expanded markedly during a cardiac cycle, M-mode registration, noting minimum and maximum diameter, was done. Negligible expansion of the ICA and ECA during systole was recorded. Because both vessels mostly run a slightly oblique course to the skin, B-mode measurements of their luminal width were more reliable than M-mode recordings. The internal diameter of these vessels was measured at

Conclusions We conclude that color duplex sonography of cerebral 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

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).

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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 \( P \leq 0.01 \) 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 insolation, 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. Side-to-Side Differences of Flow Velocities, Diameters, and Flow Volumes

<table>
<thead>
<tr>
<th>Vessel</th>
<th>n</th>
<th>Vs, 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>
</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>
</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>
</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>
</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.

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 (r=.63), CCA (r=.61; P<.0001), and ICA (r=.47; P<.001) but low in the ECA (r=.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.

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Vs</th>
<th>Ved</th>
<th>TAV</th>
<th>TAMX</th>
<th>RI</th>
<th>PI</th>
<th>SBI'</th>
<th>d</th>
<th>Flow Vol</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCA</td>
<td>-0.63*</td>
<td>-10</td>
<td>-20</td>
<td>-15</td>
<td>-.46*</td>
<td>.18</td>
<td>.58*</td>
<td>.34*</td>
<td></td>
</tr>
<tr>
<td>ICA</td>
<td>-0.40*</td>
<td>-32*</td>
<td>-23</td>
<td>-26</td>
<td>-.11</td>
<td>.02</td>
<td>.12</td>
<td>-0.8</td>
<td></td>
</tr>
<tr>
<td>ECA</td>
<td>-2.2</td>
<td>.18</td>
<td>.29*</td>
<td>.17</td>
<td>-.37*</td>
<td>-.23</td>
<td>.36*</td>
<td>.40*</td>
<td></td>
</tr>
<tr>
<td>VA</td>
<td>-3.5*</td>
<td>-22</td>
<td>-0.5</td>
<td>-22</td>
<td>-31*</td>
<td>-.18</td>
<td>.06</td>
<td>-0.1</td>
<td></td>
</tr>
</tbody>
</table>

Spearman's rank correlation coefficient is indicated. Vs indicates 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.

*P<.01; tP<.001; tP<.0001.
groups; they compared well 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 studies 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

![](image)

**Fig 2.** Scatterplot shows cerebral blood flow (CBF) measurements related to age in 47 subjects.

**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></th>
<th>Time-Averaged Velocity</th>
<th>Diameter</th>
<th>Flow Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Difference, cm/s</td>
<td>Correlation Coefficient</td>
<td>Difference, mm</td>
</tr>
<tr>
<td>CCA</td>
<td>-1.0±6.3</td>
<td>.32</td>
<td>0.2±0.6</td>
</tr>
<tr>
<td>ICA</td>
<td>-0.1±6.2</td>
<td>.25</td>
<td>0.1±0.7</td>
</tr>
<tr>
<td>ECA</td>
<td>-0.6±6.3</td>
<td>.19</td>
<td>0.4±0.5†</td>
</tr>
<tr>
<td>VA</td>
<td>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, eg, because the period of rest before the CBF measurement was shorter in the retest 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 studies, with the exception that they tended to decrease with age. In the study done by Leopold et al, 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, however, were higher (330 mL/min) and possibly due to the fact that these 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 Glover 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 Schmidt 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 al reported a mean of 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. By assuming a mean brain weight 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 duplex 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 groups have claimed that a decline occurs. Our findings reflect those of other groups, which could not establish any change in CBF due to aging.

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 studies should aid the process of defining normal and abnormal flow patterns in extracerebral and intracerebral arteries.

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Estimation of cerebral blood flow through color duplex sonography of the carotid and vertebral arteries in healthy adults.
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