Preferred Technique for Blood Flow Volume Measurement in Cerebrovascular Disease

Stella S.Y. Ho, MPhil; Constantine Metreweli, FRCR

Background and Purpose—A noninvasive reliable technique that can reveal cerebral blood flow volume could be a valuable tool in screening programs for stroke prevention. In diagnostic ultrasonography, spectral Doppler imaging (SDI) is popular among sonologists and vascular technologists to estimate blood flow volume despite its documented inaccuracy and the availability of the more accurate technique of color velocity imaging (CVI). The aim of the present study was to demonstrate the discrepancy of blood flow volume estimation with CVI and SDI with use of an “internal” standard.

Methods—The common, internal, and external carotid arteries of 50 healthy subjects (22 men, 28 women, age range 19 to 54 years) were examined with CVI and SDI. The total blood flow volume of the internal and external carotid arteries was then compared with the ipsilateral common carotid artery flow. An accurate technique would demonstrate no difference. The difference (expressed as a percent inconsistency) was therefore a measure of the accuracy of the method.

Results—The mean±SD inconsistency was found to be 10.6±8.3% for CVI and 27.9±14.3% for SDI. The difference in inconsistency between CVI and SDI in measurement of carotid blood flow volume was statistically significant (P<0.01).

Conclusions—CVI is more accurate than SDI in the determination of blood flow volume in the carotid arteries. For noninvasive clinical estimation of cerebrovascular blood flow volume, CVI quantification should be the preferred technique. (Stroke. 2000;31:1342-1345.)

Key Words: cerebral blood flow ■ cerebral ischemia ■ ultrasonography, Doppler

Quantification of carotid blood flow volume (BFV) is clinically useful because it allows hemodynamic evaluation of a carotid stenosis and its collateral pathways,1,2 assessment of cerebrovascular reserve capacity and prediction of prognosis,3 estimation of the shunt volume in cerebral arteriovenous malformations,2,4 and monitoring of cerebral blood flow before and after carotid endarterectomy.4,5 Therefore, a technique that would most accurately reveal this information would be of great value in patients with cerebrovascular disease.

Even though in vitro and in vivo tests have shown that color velocity imaging (CVI) is accurate in the measurement of BFV6–8 and that spectral Doppler imaging (SDI) tends to significantly overestimate it,9 SDI is still used by sonologists.

In this regard, the present study was undertaken to demonstrate the discrepancy of BFV estimations with CVI and SDI. An in vivo “internal” validation of these 2 techniques was performed to determine the carotid BFV in a group of healthy subjects, to compare the accuracies of these 2 techniques, and to justify their applications in clinical practice.

Subjects and Methods

The BFV estimates of 100 groups of extracranial carotid arteries were obtained with CVI and SDI in 50 healthy subjects aged from 19 to 54 years (22 men, 28 women). None of the subjects had a known history of hypertension, heart disease, diabetes mellitus, or smoking.

This study was performed based on the assumption that total BFV of the internal carotid artery (ICA) and external carotid artery (ECA) was equal to that of the common carotid artery (CCA). Any measurement of difference would then reflect the inconsistency of the imaging technique applied. All 3 blood vessels (ie, CCA, ICA, and ECA) of the 100 groups of extracranial carotid arteries were examined with the high-resolution 7.5-MHz linear probe of the Philips SD800 ultrasound scanner (Philips Ultrasound International). This device has a standard feature with the capability of both CVI with flow quantification (CVIQ) and pulsed Doppler imaging. Each blood vessel was in turn interrogated with CVI and SDI in the straight segment at least 2 cm from the bifurcation. The measurements were repeated 3 times and averaged to provide the BFV estimates for each vessel.

With the technique of SDI, a large Doppler sample volume that corresponds to the vessel diameter was used to determine the approximate mean velocity. The anatomic vessel diameter was measured as close to the line of interrogation as possible (Figure 1).

The BFV was calculated with the equation BFV=mean velocity×vessel cross-sectional area=mean velocity×π/4×(vessel diameter)².

To determine the BFV with the CVI technique, a color box of a size that covered the entire luminal cross section was used. The image was adjusted with optimal color saturation with no aliasing or color “bleeding” over the lumen. The color image was synchronized with the M-mode, which can provide simultaneous information...
about functional vessel diameter during the cardiac cycle and multirange gated velocity information. The BFV was automatically computed with the built-in system software after the color M-mode image was frozen (Figure 2). An identical angle correction of 60° was applied to all vessels in both techniques.

With each technique, the sum of ICA and ECA BFVs on each side was compared with that of the ipsilateral CCA. The inconsistency of each technique was expressed as the percent difference between the sum of ICA and ECA BFV estimates and that of the CCA. It was calculated by subtracting the total ICA and ECA blood flow by the CCA flow. The absolute difference was then divided by the CCA flow and expressed as a percentage. The paired *t* test was used to compare the percentage inconsistency of the two techniques. The significance level was taken at *P* < 0.01.

Because CVIQ is a relatively new technique for measurement of BFV in contrast to the more popular and conventional SDI technique, interobserver and intraobserver variabilities for this technique were determined. The BFV of 32 CCAs of an additional 16 normal volunteers (8 men and 8 women, age range 18 to 49 years, average age 33.2 years) were measured by 3 operators (A, B, and C). Ten readings of BFV for each CCA were made by each operator, blinded to the results of the others. The results were then analyzed with the Friedman test for intraobserver variability and Kendall’s W test for interobserver variability. The significance level was set at *P* < 0.01.

**Results**

The BFV estimates of 100 groups of carotid arteries were successfully obtained from 50 healthy subjects with both CVI and SDI techniques (Table 1). The discrepancy in percent inconsistency (±SD) between the 2 techniques was significant (*P* < 0.001) with lower inconsistency in CVI (10.6 ± 8.3%) than in SDI (27.9 ± 14.3%).

Although there was a significant difference in the BFV between CCA and its branches (ICA + ECA) obtained with either technique (*P* < 0.001), there was better correlation of the CCA BFV with the sum of (ICA and ECA) BFV with the CVI technique than with the SDI technique (Figures 3A and

**Figure 1.** BFV measurement in the CCA with SDI. The measurement was made in a straight segment with a large sample volume that encompassed the vessel lumen. The vessel diameter was measured close to the line of interrogation.

**Figure 2.** BFV measurement in the CCA with CVI. The BFV was automatically computed from the color M-mode trace after the image was frozen.
3B). With both techniques, the blood flow estimates were consistently greater for CCA than for the sum of its branches.

The interobserver ($P=0.8825$) and intraobserver variabilities of the 3 operators ($P=0.7619$ for A, $P=0.5610$ for B, and $P=0.5432$ for C) in measurement of BFV with CVIQ was insignificant ($P>0.01$).

**Discussion**

On the basis of the equation of BFV measurement, 2 determinants that affect the BFV quantification are the temporal mean flow velocity and the temporal vessel diameter. Any error in the determination of these parameters will result in faulty BFV estimates.

### Table 1. BFV estimates of CCA, ICA, and ECA With CVI and SDI Techniques

<table>
<thead>
<tr>
<th>Vessel</th>
<th>BFV With CVI</th>
<th>BFV With SDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCA</td>
<td>340.9±75.6</td>
<td>672.8±152.9</td>
</tr>
<tr>
<td>ICA</td>
<td>226.9±65.0</td>
<td>316.2±89.1</td>
</tr>
<tr>
<td>ECA</td>
<td>92.2±36.7</td>
<td>183.5±90.8</td>
</tr>
<tr>
<td>ICA+ECA</td>
<td>319.1±76.2</td>
<td>497.9±146.9</td>
</tr>
</tbody>
</table>

Values are mean±SD, in milliliters per minute.

Diameter Measurement

This study showed that both CVI and SDI techniques were inconsistent in estimations of BFV, but the mean percent inconsistency was less for CVI ($≈11\%$) than for SDI ($≈28\%$). Other experimental studies have also shown that CVIQ produces better consistency than SDI.$^{9,10}$ The error of SDI mainly comes from erroneous diameter measurement on a static gray scale image, with the assumption of a stable vessel. It must be emphasized that small errors in the diameter measurement will result in large errors in the calculation of cross-sectional area and, hence, flow volume. Because the physiological anatomic diameter in systole or diastole varies and may differ by as much as $10\%$, the diameter variation alone can account for flow volume errors of up to $20\%$. The unique feature of the acquisition of simultaneous information about functional diameter and multirange gated velocities of the CVI technique ameliorates the problem with SDI for measurement of BFV.

Angle Correction

Angle correction is essential for flow velocity and diameter calculations that may affect the accuracy of BFV estimation with both techniques. Unfortunately, a favorable insonation angle for diameter measurement is adverse for flow velocity

![Figure 3. BFV estimates with CVI (A) and SDI (B). The BFV of the CCA was plotted against that of the ICA and ECA. A much better correlation was obtained with CVI.](http://stroke.ahajournals.org/doi/fig/10.1161/01.STR.34.6.1344/fig-3)
estimation. Normal incidence of the ultrasound beam produces echoes of the shortest duration and greatest amplitude, so true vessel diameter measurement is ideal at an angle of 90° with little error. At this large angle of incidence, even a 2° error can result in unacceptably high error in the volume flow determination. Imaging at an angle of <90°, however, will tend to underestimate the vessel diameter due to the effect of beam width. As a compromise, an angle correction of 60° was standardized for BFV measurement with both techniques. Angle correction error was likely to account in part for the internal inconsistency of each technique but would be of similar magnitude for both.

### Turbulent or Disturbed Flow

Often, helical or disturbed flow is present near the bifurcating point, making the relationship between the angle of the beam with the velocity vectors even more uncertain. This inherent uncertainty will contribute to an inconsistent BFV estimate. To reduce the uncertainty, a straight vessel segment at least 2 cm from the bifurcation should be interrogated. In practice, this kind of error is sometimes unavoidable. This error particularly affects the ECA BFV measurement when the prebranching segment of the ECA near the carotid bulb had to be chosen to validate the test.

### Off-Axis Sampling

Off-axis sampling is a significant error in subjects with respiratory movement of the carotid arteries or in pulsatile vessels. The off-axis error simultaneously causes a velocity error by missing the central peak flow velocities and underestimating the true vessel diameter, with resulting large errors in BFV estimates.

Of the many potential sources of error, most seem to be common to both techniques (Table 2). Temporal change in diameter and improved quantification of both temporal changes in velocity and differences of velocity across the vessel at any point in time are better estimated with CVIQ, and this is probably one of the major contributions to its accuracy for BFV. With SDI, if a time-averaged M-mode measurement for the vessel diameter is used, the error can be minimized. Where M-mode is not available, the measurements can be repeated several times and averaged to reduce the random error to an acceptable level. However, this is time consuming and less accurate than the automated CVIQ method.

A further validation that CVIQ is more accurate than SDI can be derived from the prediction of brain mass with these 2 techniques. It has been shown that mean regional cerebral blood flow is ≈50 mL·100 g⁻¹·min⁻¹. If we assume that nearly all of the CCA flow perfuses the brain, the brain weight predicted with CVIQ (total CCA BFV was ≈680 mL/min) is 1.36 kg. The same calculation with SDI (total CCA BFV was ≈1340 mL/min) yields 2.68 kg. Current estimates of brain weight with CVIQ far more closely approximate the values of human brain weight (men ≈1.5 kg, women ≈1.3 kg) quoted in the literature.

This study was performed on young normal subjects with promising results on CVIQ. Although difficulties may be encountered in elderly patients in reproducing similar results due to diseased arteries, vessel tortuosity, arrhythmia, or poor patient condition, CVIQ remains a suitable technique for noninvasive clinical estimation of cerebrovascular BFV and should be the preferred technique.

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