Carotid Artery Velocity Patterns in Normal and Stenotic Vessels

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SUMMARY Duplex scanning provides real time B-mode images of the carotid bifurcation vessels along with a single gate pulsed Doppler flow velocity detector. By using the B-mode output of the duplex system to measure the Doppler angle and spectrum analysis to measure the frequency content of the Doppler signal, instantaneous flow velocity can be calculated.

Mean velocity at peak systole was calculated retrospectively in 68 common (CCA) and internal (ICA) carotid arteries of 39 patients who had undergone prior angiography and prospectively in 30 arteries of 15 healthy young controls. The ratio of mean peak ICA velocity to mean peak CCA velocity at systole (VICA/VCCA) was below 0.8 in all 36 normal arteries and above 1.5 in all 21 high-grade stenoses of 60% or greater diameter reduction. Sixty-one percent of 41 vessels with less than 10 to 55% diameter reduction had a velocity ratio between 0.8 and 1.5. Only 10% of all ICA's with any stenotic lesion were incorrectly classified as normal. VICA/VCCA appears to be an accurate indicator of the degree of ICA stenosis.

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THE MOST COMMONLY USED techniques for noninvasive evaluation of the extracranial carotid circulation will detect only those lesions which reduce distal pressure and flow. These include the oculophtysmographic1-2 and supraorbital Doppler3-4 methods although the reported accuracy of these tests has varied considerably.1,4,5,6 The recent development of ultrasonic imaging techniques (table 1) has spurred new interest in direct visualization of the carotid bifurcation.

We use in our laboratory an ultrasonic duplex scanner which provides simultaneous real time B-mode arterial images and a single gate pulsed Doppler flow to detect velocity changes.18 The velocity information is evaluated using a spectrum analyzer which permits quantification of the frequency content of the reflected Doppler signal.16,17 Although our work in this area is ongoing, it became apparent during these studies that instantaneous velocity information could be of value in estimating the degree of stenosis. Since the velocity of flow through a stenosis is related to the degree of narrowing, this variable was investigated in a series of patients who had undergone arteriography.

Materials and Methods

I. Theoretical Considerations

As an atherosclerotic plaque progressively narrows the lumen of a vessel, the velocity of flow at that site must increase if constant flow is to be maintained (fig. 1). Even when volume flow is reduced distal to a high-grade stenosis, the velocity of flow within the stenosis itself is elevated. Therefore, flow velocity is proportional to the cross-sectional area of the arterial lumen at the site of measurement. However, instantaneous flow velocity is influenced, among other things, by vessel size and elasticity, myocardial contractility, and cardiac output, and these parameters may vary considerably from one patient to another. Considerable overlap in absolute velocity measurements might thus be expected.

For the case of steady flow in a cylindrical tube which bifurcates into 2 branches of equal area, mean flow velocity in a branch bears a constant relationship to the velocity in the parent tube.18 This relationship suggested that there may be a relatively constant relationship in instantaneous flow velocity between an internal carotid artery (ICA) and its parent common carotid artery (CCA) even though the situation at the carotid bifurcation is much more complex. For example, the external and internal carotids are not of equal area, they perfuse beds of different resistances, and flow is pulsatile, not steady. The ratio of ICA velocity to its parent CCA velocity could then decrease the influence of the aforementioned factors affecting absolute velocity, since they should be relatively constant for both CCA and ICA.

II. Study Protocol

The duplex scanner combines B-mode imaging with a 5 MHz single-gated pulsed Doppler.19 Carotid examination is performed by placing the scan head on the neck along the axis of the carotid vessels. Real time B-mode arterial images (fig. 2) are generated on a television screen and are used as a guide for placement of the pulsed Doppler sample volume within the arterial lumen to assess flow characteristics. The B-mode image and the Doppler signal from each location examined are recorded on video tape. Spectrum analysis can then be used to measure the frequency shift of the reflected Doppler signal at any point in the pulse cycle (Honeywell fast Fourier transform spec-
TABLE 1  Ultrasonic Evaluation Techniques

<table>
<thead>
<tr>
<th>Ultrasonic imaging</th>
<th>Signal processing</th>
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<tbody>
<tr>
<td>1. Doppler flow imaging</td>
<td>1. Spectrum analysis</td>
</tr>
<tr>
<td>a. Continuous wave</td>
<td>a. Doppler signal</td>
</tr>
<tr>
<td>b. Pulsed</td>
<td>b. Bruit</td>
</tr>
<tr>
<td>2. B-mode imaging</td>
<td></td>
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<tr>
<td>3. Duplex scanning</td>
<td></td>
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</table>

The spectrum from a normal internal carotid is shown in figure 3. High-grade stenoses exhibit higher peak frequencies associated with opacification of the area under the systolic peak caused by elevated flow velocity and disturbed flow. In every case, the sample gate in the ICA was positioned at the point of the maximum velocity change.

The frequency of the Doppler shifted signal (Fd) is related to the velocity (V) of the red blood cells within the pulsed Doppler sample volume by the Doppler equation:

$$CFd = 2VF0 \cos \theta$$

where C = constant related to the speed of sound in tissue ($15.4 \times 10^6$ cm/sec), $F0$ = frequency of the incident Doppler beam ($5 \times 10^6$ Hertz), and $\theta$ = Doppler angle between the incident beam and the axis of flow. Since $\theta$ can be measured from the B-mode image of the duplex system and Fd can be measured from the output of the spectrum analyzer, the instantaneous velocity of flow, V, at any time during the cardiac cycle, can be calculated with the data available.

Sixty-eight vessels in 39 patients who had been previously studied with the duplex scanner and had undergone subsequent selective 4-vessel multiview (biplane) carotid arteriography were selected for the retrospective review (Group I). Ten of these patients had a unilateral ICA occlusion. All arteriograms had been independently interpreted by 2 radiologists who were unaware of the results of duplex scanning. Vessels were graded by percentage reduction of their projected normal angiographic diameter. Vessels with wall irregularity without a definite constricting plaque were classified as having less than 10 percent stenosis. Although a 50% diameter stenosis, which is equivalent to a 75% area reduction, is considered to be the point at which carotid flow is reduced,20,21 in this study only those lesions of 60% or greater radiographic diameter reduction were grouped as high-grade, or flow reducing, stenoses. Vessels from less than 10 to 55% diameter reduction were considered low-grade lesions. The reason for the distinction at this point was that for several of the vessels in the range of 45–55% stenosis, there was disagreement between our two radiologists about the exact degree of diameter reduction, necessitating arbitration. This uncertainty around the area of 50% stenosis was reflected in the velocity data, which shows some overlap between velocity ratios characteristic of high-grade and low-grade stenoses. Thus, only those vessels which harbored lesions that were unequivocally flow reducing were grouped as high-grade stenoses.

Since the number of completely normal vessels in Group I was low, a second group was studied prospectively, consisting of 30 arteries in 15 healthy young control subjects under the age of 35 without evidence of arterial disease (Group II). All of these subjects were classified as normal although none was studied by angiography.

Doppler angles were measured from the B-mode image of the video tapes for several recordings from each CCA and ICA (fig. 3). The average instantaneous frequency at peak systole was then measured from the output of the spectrum analyzer (fig. 4). Peak systole was selected since it was a clearly definable point in each pulse cycle and it also was the time when velocity changes were most apparent.

The highest systolic velocity was calculated for each

$$Q_1 = A_1 V_1$$

$$Q_2 = A_2 V_2$$

$$Q_2 = Q_1$$

$$A_2 < A_1$$

$$V_2 > V_1$$

FIGURE 1. Relationship between the cross-sectional area of an artery and its effect on volume flow and velocity when a stenosis is present. $Q$ = volume flow, $A$ = cross-sectional area, $D$ = diameter.
CA VELOCITY PATTERNS/Blackshear et al.

FIGURE 3. Spectrum from a normal internal carotid at the point marked by the arrow. The peak systolic frequency is low and the area under the systolic peak is clear, indicating no evidence of disturbed flow at this site.

FIGURE 4. Calculation of the average instantaneous frequency at peak systole. $MF$. Instrument effects, as well as flow disturbances, produce broadening of the pulsed Doppler frequency spectrum so that the peak frequency does not reflect the actual velocity of flow within the sample gate. $MF$ is probably a more accurate representation of the flow velocity at peak systole.

CCA and ICA from the Doppler equation. The ratio of the highest mean ICA velocity to the highest mean CCA velocity, $VICA/VCCA$, was also calculated for each side. This ratio was plotted against the percentage of angiographic diameter stenosis.

Results

The range of absolute velocity measurements in the ICA and the CCA for each of the 3 angiographic categories is shown in table 2. While the CCA velocity tends to decrease and the ICA velocity to increase as the degree of stenosis becomes more marked, there is considerable overlap among the categories, confirming the difficulty in using absolute velocity data for quantitation.

Figure 5 illustrates $VICA/VCCA$ in the normal arteries in Group II. In none of these vessels did this ratio exceed 0.8 and in most it ranged from 0.4 to 0.7.

The relationship between the velocity ratio and the percentage stenosis is shown in figure 6. In the 6 normal vessels $VICA/VCCA$ was again below 0.8. Combining these vessels with those in Group II gives a total of 36 normal vessels in which the velocity ratio

<table>
<thead>
<tr>
<th>Carotid lesion</th>
<th>Common carotid</th>
<th>Internal carotid</th>
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<tbody>
<tr>
<td>Normal</td>
<td>25.0-112.0</td>
<td>20.1-112.0</td>
</tr>
<tr>
<td>&lt;10-55% Stenosis</td>
<td>33.2-121.5</td>
<td>24.1-209.8</td>
</tr>
<tr>
<td>60-99% Stenosis</td>
<td>47.0-114.1</td>
<td>93.5-304.6</td>
</tr>
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was shown to be under 0.8. In all 21 high-grade stenoses this ratio was above 1.5 and in most it was much higher.

There were 41 vessels in the low-grade stenosis category and in 25 of these (61%) the velocity ratio was between 0.8 and 1.5. In 7 (17%) of these vessels VIca/VCCA was over 1.5 and in nine (22%) it was below 0.8. However, 3 of the latter vessels were in the less than 10% stenosis category which had no definite stenotic plaque, only wall irregularity, and thus might be expected to have a velocity ratio much like that of normal vessels. Eliminating the 4 arteries with less than 10% stenosis from consideration improves the accuracy of correct classification of low-grade lesions to 64.9% (28 of 37). Six of these 37 vessels (16.2%) had a velocity ratio below 0.8, placing them within the normal range. In 7 vessels (18.9%) the velocity ratio indicated more severe disease than was seen on the angiogram. Only 6 of the 58 ICA's (10.3%) with a definite stenotic lesion between 10% and 90% diameter reduction were incorrectly classified as normal.

Discussion

This retrospective study demonstrates the feasibility of using velocity data obtained transcutaneously by ultrasonic techniques to estimate internal carotid stenoses. The velocity ratio, VIca/VCCA, discriminated between normal, low-grade, and high-grade stenoses much better than the absolute velocity measurements. All of the high-grade stenoses (>60% diameter reduction) were correctly classified, as were all normal vessels, both angiogrammed and control. Sixty-one percent of the low-grade lesions (<10-55% stenosis) were correctly classified, and a stenosis was missed in only 10% of the vessels with a definite plaque. These results were reproducible upon repeat study of several of these patients.

From figure 6, VIca/VCCA appears to increase linearly as the degree of stenosis increases, although there is some scatter in the data points. There are 4 factors which may contribute to this variability. First, the ICA Doppler signal must be recorded precisely from the point of maximum stenosis to detect the maximum velocity increase. Second, the configuration of the plaque may well influence the flow pattern in the stenosis. In this study no attempt was made to distinguish between sharp, discrete stenoses and long, irregular plaques. Third, the degree of external carotid (ECA) stenosis may well influence the CCA peak velocity. It is somewhat more difficult to produce a reliable image from the external than from the internal carotid with the duplex system, so accurate velocity data from the ECA were not available on many sides. The ECA should probably be taken into account in future trials of this method, however.

Finally, as indicated earlier, when attempting to quantitate the degree of ICA stenosis, the error inherent in interpreting angiograms is a problem that must be recognized. The inter- and intraobserver variability may approach 20% of vessels when evaluating the ICA. This problem was most evident in our study in several vessels with stenoses in the range of 50% diameter reduction in which our 2 radiologists disagreed about the exact percentage of stenosis. In these vessels, the anatomic data provided by the angiogram did not correlate well with the physiologic data provided by the velocity ratio. The simultaneous B-mode image and Doppler signal of the duplex system is quite convenient for velocity calculations; however, the same sort of data could be obtained with other Doppler systems which...
include a method for measuring the Doppler angles. We have found Doppler frequency measurements alone to often be misleading for this sort of calculation since the proximal portion of the ICA usually courses at a different angle than the CCA and this angle varies with patients. The Doppler shifted frequency we recorded from the proximal ICA was usually higher than that from its parent CCA in normal subjects; however, this apparent increase in velocity in the ICA was an artifact induced by the smaller ICA Doppler angle. When the correction for angle was applied, the actual decrease in ICA velocity became apparent. The ability to measure the Doppler angle for velocity calculations, rather than relying on frequency measurements, is therefore important.

In making the determinations, it is critically important that the sample volume be placed in the area of maximum velocity change in the internal carotid artery. This was done to insure that the data were taken from the point of greatest narrowing. Clearly, if this were not done, i.e. a sample was taken at some point distal to the stenosis, the peak velocity would be lower as would the ratio used in our calculations.

Determination of the place of this sort of physiologic data in the evaluation of ICA disease awaits prospective studies, although the results of this retrospective survey are encouraging. They suggest that \( V_{ICA} / V_{CCA} \) is an accurate and reproducible indicator of the degree of ICA stenosis and that this velocity data is more useful than Doppler frequency measurements. Not only can flow reducing stenoses be accurately detected by this method, but many plaques which are not large enough to reduce distal pressure and flow but which may be the site of intimal ulceration can also be identified. It must be emphasized, however, that data are not yet available to show that ulceration can be detected by this approach.

In summary, duplex scanning and pulsed Doppler spectrum analysis were used for velocity calculations retrospectively in a group of patients studied by angiography and prospectively in a control group. The ratio of peak systolic velocity in the internal carotid artery to that in its parent common carotid artery was found to be an accurate indicator of the degree of internal carotid stenosis, separating normal vessels from stenotic ones and permitting accurate categorization of most stenoses as high-grade (flow reducing) or low-grade (non-flow reducing) lesions.

References
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