Pulsed Multigated Doppler Ultrasonography in the Diagnosis of Carotid Artery Disease

Henrik Sillesen, MD, Karen R. Bitsch, MD, Torben Schroeder, MD, Hans Jørgen Steenberg, MD, MSc, Linda Hansen, VT, and Hans Jørgen Buchardt Hansen, MD, PhD

To evaluate the accuracy of a pulsed multigated Doppler system, 128 carotid arteries were examined. The spectral broadening index was calculated from the power spectrum of a small sample volume located in the center of the stream according to the flow profile and was related to the degree of stenosis as determined by contrast angiography. Even minor wall irregularities seen on the angiogram were classified as disease. The ability of the system to discriminate between normal and diseased vessels reached a sensitivity of 94% and a specificity of 91%. Classification of >50% or <50% stenosis could be performed with a sensitivity of 90% and a specificity of 85%. Pulsed multigated Doppler ultrasonography allows identification of even minor degrees of stenosis of the carotid artery and provides an alternative to duplex scanning. Furthermore, the blood flow profile provided by a multigated Doppler system may add valuable information concerning blood flow characteristics not obtainable by single-gated systems. (Stroke 1988;19:846-851)

It is generally accepted that with most of the Doppler techniques presently available, vascular lesions with substantial narrowing of the lumen (>50% diameter reduction) can be detected accurately. In addition, differentiation between tight stenosis and occlusion can be made. The diagnosis of less pronounced degrees of stenosis, however, has caused difficulties. Using continuous-wave (CW) Doppler ultrasonography, we have previously found the spectral broadening index (SBI) as defined by Kassam et al to be an accurate predictor of all degrees of carotid artery disease. However, for the exclusion of minor lesions a more sensitive method is required. In this respect, recent reports have suggested that pulsed-wave Doppler systems have advantages over CW Doppler equipment.3–8

As stand-alone equipment, single-gated pulsed-wave Doppler ultrasound is difficult to handle due to orientation problems. The use of four to six gates sampling simultaneously has been offered in the position-sensing-arm systems. Reneman and Hoeks9 have described the simultaneous use of multiple gates. From the zero-crossing frequencies of all the gates a real-time flow profile can be generated. This profile can be used for orientation within the vessel, for diameter measurements, and for assessment of flow velocity disturbances. However, reports on the clinical applicability of such a system for evaluating carotid artery disease are limited.7,10 In addition, objective quantification of pulsed-wave Doppler spectral broadening has been seldom reported.5,11

The purpose of our study was to evaluate the accuracy of 128-gated pulsed-wave Doppler equipment for detecting carotid artery disease, using the velocity profile to orient the sample volume for spectral analysis. From the power spectrum, the systolic SBI was calculated and related to arteriographic degree of stenosis.

Subjects and Methods

Subjects

A series of 68 consecutive patients (median age 61, range 37–78 years) was examined with arteriography and pulsed-wave multigated Doppler ultrasonography. Both examinations were performed within a period of 4 weeks. All patients were referred to the Department of Vascular Surgery for evaluation of carotid artery disease. In 54 patients the indication for arteriography was cerebrovascular symptoms, and an asymptomatic cervical bruit was present in 14 patients. In five patients arteriography was performed only unilaterally, and in three patients...
FIGURE 1. Top: Normal flow profile derived from multigated Doppler system. New line is drawn every 80 msec, and mean frequency is displayed in horizontal direction. Depending on heart rate, two to five cardiac cycles may be displayed simultaneously. Systole (S) and diastole (D) are indicated. Horizontal line indicates location of sample volume used for fast-Fourier transformation. Bottom: Spectrum obtained from sample volume located in center of stream according to horizontal line in top.

the taped Doppler examinations on one side were of poor quality, making analysis impossible. This left 128 arteries available for comparison.

Ultrasound Examination

Examinations were carried out with a Doppler prototype (Copenhagen, Denmark) capable of both CW and pulsed-wave multigated Doppler ultrasound. A 5-MHz transducer with the focal point 1–3 cm from the crystal was used for all examinations. In the pulsed-wave multigated mode this equipment can provide 128 simultaneous gates. The zero-crossing frequencies from all gates are displayed one on top of the other in the vertical direction, with the Doppler shift displayed in the horizontal direction (Figure 1, top). This profile is updated every 80 msec. In this manner a real-time flow profile is provided. The Doppler shift from one sample volume can be analyzed using a frequency analyzer. This sample volume, indicated by the horizontal line (shown in Figure 1, top) can be moved up and down to place it where appropriate. The magnification of the flow profile can be changed as to the location of the vessel examined. It is easy to identify systole from diastole.

FIGURE 2. Flow profile obtained from normal internal carotid artery bulb. Note retrograde blood flow occurring only during systole located near far vessel wall (arrows).

Patients were examined in the supine position. With the Doppler equipment in CW mode, the common carotid artery (CCA) was located just above the clavicle, and oriented cranially, the transducer was advanced along the CCA with continuous audible interpretation of the Doppler signal. The angle between the transducer and the skin surface was ideally kept between 40° and 60°. When the internal carotid artery (ICA) was located, the pulsed-wave multigated mode was switched on, and the sample volume for frequency analysis was placed in the center of the vessel according to the flow profile (Figure 1, bottom). If the profile was asymmetric due to flow separation (normal in the carotid bifurcation; Figure 2), the sample volume was placed where the flow velocity was highest. From this location in the carotid bulb the transducer was advanced carefully as far distally as possible, making sure that sampling was made from the center of the stream. From the proximal to the distal ICA, at approximately 0.5–1-cm intervals, 10–15 heart beats were recorded on a Technics RS-B48R tape recorder. The external carotid artery (ECA) was also insonated and identified by tapping on the superficial temporal artery; however, no findings were recorded from this artery.

Signal Processing

After all examinations had been performed, the taped Doppler signals were analyzed with a Danish spectrum analyzer prototype without knowledge of the arteriographic findings. Every 9 msec a new spectrum was generated with 256-point fast-Fourier transformation (FFT) analysis. From the power spectrum the analyzer calculates the minimum, mean (F_median), and maximum (F_max) frequencies and the SBI [(F_max - F_median)/F_max]. Memory of the last three screens of analyzed Doppler signals was available. F_max was defined as the frequency below which 90% of the power spectrum was found. Based on the results of Douville et al. and Sillesen et al. the systolic SBI was used. In a normal carotid artery frequency spectrum, the systolic SBI is lower than diastolic SBI (Figure 3, top), whereas in the pres-
ence of turbulent blood flow distal to an 80% stenosis, systolic SBI becomes higher than diastolic (Figure 3, bottom). This clearly indicated that systolic SBI was the more sensitive parameter. Systole was defined from the beginning of the acceleration phase to late in the deceleration phase. Only positive Doppler signals (blood moving toward the brain) were analyzed since the spectrum analyzer used was incapable of analyzing bidirectional signals simultaneously. The SBI used for comparison with arteriography was that obtained from the location giving the highest SBI, averaged over at least three cardiac cycles, from the same location.

**Arteriography**

The four-vessel conventional two-plane arteriograms were read by an experienced radiologist unaware of the Doppler results. Degree of stenosis was defined as \%stenosis = 100 \( \times \) (A - B/A) where B is the diameter of the vessel at the point of maximum stenosis and A is the normal vessel diameter distal to the stenosis.

**Analysis of Results**

True positive and false-positive ratios were calculated for a number of different SBI values and plotted against each other in receiver operator characteristic (ROC) curves. From these curves the SBI values were chosen that were most accurate in discriminating between disease and no disease and for classifying stenoses as >50% or <50%.

**Results**

Ten ICAs were occluded, and all were correctly classified. However, two ICAs were mistakenly classified as occluded since no Doppler signal could be obtained. One was hypoplastic, with a diameter of <2 mm, and the other showed a 13% stenosis. The results in these 12 vessels have been omitted from the illustrations since no SBI could be calculated.

Figure 4 shows the relation between SBI and arteriographic degree of stenosis. Although some scattering was observed, a correlation is obvious. The ROC curve to discriminate between disease and no disease is shown in Figure 5. With an SBI of 0.20, a sensitivity of 94% and a specificity of 90% were obtained (Table 1). The ability of SBI to discriminate between >50% and <50% stenosis was evaluated similarly, and the results are shown by the ROC curve in Figure 6. Using an SBI of 0.37 as a discriminating value, a sensitivity of 90% and a specificity of 85% were reached (Table 2).

Combining the two SBI values, the arteries could be separated into three groups: normal, stenosis of <50%, and stenosis of >50%. The overall agreement with arteriography was 80% (Table 3). Most disagreements (16 of 24) occurred between the two groups with stenoses of >50% and <50% (Figure 4). In no instance was stenosis of >50% classified as normal or was a normal vessel classified as severely diseased.

**Discussion**

Pulsed-wave Doppler ultrasonography has been used in the diagnosis of carotid artery disease reaching accuracies of 90%. The results obtained in studies using duplex scanners seem superior to those from studies using either a position-sensing arm or single-gated pulsed-wave Doppler alone. In most reports dealing with duplex scanners, the B-mode image has been used only for guiding the Doppler sampling volume into the location of interest. The degree of stenosis is evaluated from the FFT Doppler shift in spite of the potential of visualizing even minor lesions using the B-mode image. On the other hand, problems emerge using B-mode scanning alone in the discrimination between severe stenosis and occlusion. Our results are comparable with those reported with duplex scanning, in terms of both identifying minor lesions and overall agree-
This is interesting since the sampling of Doppler signals was guided by the real-time flow profile; no direct visualizing technique was used. In favor of the method we describe is the fact that the flow profile is asymmetric at arterial bifurcations, as shown in Figure 2. Blood flow disturbances may be present even in normal bifurcations. Hence, anatomic positioning may lead to sampling from locations other than the center of the stream. On the other hand, the use of a nonvisualizing technique does not allow for identification of minor lesions having smooth surfaces not disturbing blood flow in the vessel. In fact, it has been suggested that early atherosclerotic deposition may just fill the carotid bulb, resulting in the disappearance of blood flow separation, thus leaving flow patterns very uniform. Using the present approach in which the blood flow profile was used only to guide the sample volume and not to identify certain profile shapes, false-negative results would be encountered. Furthermore, it is not possible to assess the composition of the plaque, which may have prognostic significance. B-mode imaging, on the other hand, has been shown to be accurate in the assessment of plaque composition compared with surgical specimens.

The variation in spectral width that occurs when the sample volume is moved across the vessel has previously been described by Phillips and coworkers. This variation is due to the parabolic shape of the blood flow profile in the carotid artery (Figure 1). As mentioned, flow separation occurs in the normal carotid bulb during systole, opposite the flow divider. Therefore, inaccurate positioning of the sample volume could account for some variation in SBI, especially if the sample volume is placed in the area of systolic flow reversal. However, we tried to avoid this problem by placing the sample volume at the location of highest forward velocity. The distance from the stenosis should also be considered since SBI has been shown to decline as the distance from the stenosis increases. Also, blood flow volume may influence the degree of blood flow disturbance in both normal and diseased vessels. The magnitude of a possible pressure gradient across the stenosis as well as irregularities of the plaque may affect the Doppler spectral broadening, but this possibility has not been investigated. These factors can account for the considerable variation in SBI produced by lesions occlud-


TABLE 2. Spectral Broadening Index for Pulsed-Wave Multigated Doppler Ultrasonography Related to Arteriography

<table>
<thead>
<tr>
<th>Spectral broadening index</th>
<th>Arteriography</th>
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<tbody>
<tr>
<td></td>
<td>Stenosis</td>
</tr>
<tr>
<td></td>
<td>&lt;50%</td>
</tr>
<tr>
<td></td>
<td>≥50%</td>
</tr>
<tr>
<td>Value</td>
<td></td>
</tr>
<tr>
<td>&lt;0.37</td>
<td>74</td>
</tr>
<tr>
<td>≥0.37</td>
<td>13</td>
</tr>
<tr>
<td>Accuracy</td>
<td></td>
</tr>
<tr>
<td>Sensitivity</td>
<td>90% (26/29)</td>
</tr>
<tr>
<td>Specificity</td>
<td>85% (74/87)</td>
</tr>
<tr>
<td>Positive predictive value</td>
<td>67% (26/39)</td>
</tr>
<tr>
<td>Negative predictive value</td>
<td>96% (74/77)</td>
</tr>
</tbody>
</table>

Occluded arteries omitted from discrimination of <50% from ≥50% stenosis.

ing the vessel to the same degree (Figure 4). Thus, quantitative assessment of Doppler spectral broadening may not be ideal for accurate differentiation of all degrees of stenosis. Especially in the grading of severe lesions (>70–80%), it appears less accurate. Other methods for identifying these lesions have been shown to be accurate.26

Most reports on pulsed-wave Doppler ultrasonography for carotid diagnostics have used visual interpretation of Doppler spectra, and excellent results have been reported in the hands of experienced investigators. An objective quantification of the blood flow disturbances, however, as used in our present study, poses obvious advantages.21,22

Postexamination analysis of the Doppler signals can create some test errors. Disagreements between the audible interpretation of the examination and the calculated SBI will not be noticed. Another problem of our study was that only Doppler signals from a single gate were stored on magnetic tape. The flow profile, indicating from where Doppler shifts were sampled, was not stored since this would have required either a multichannel tape recorder (128 channels) or a series of photographs matched to all recording sites. The ideal use of SBI should therefore include real-time calculation of the index.

Finally, the gold standard, arteriography, is subject to interobserver variability,27,28 which may explain some of the disagreement observed. Variations of half a millimeter in measuring the degree of stenosis can misclassify a stenosis by 10–20%. This

FIGURE 7. Flow profile obtained from internal carotid artery with severe (65%) stenosis. Note difference from Figure 1, top.

may be the reason why approximately two thirds of all disagreements were between stenoses classified as >50% or <50%.

We have reported on retrospective processing of CW Doppler signals.2 The diagnostic accuracy concerning severe stenoses (≥50%) was identical to our present results obtained by pulsed-wave multigated Doppler ultrasonography. As expected, the ability to discriminate minor lesions from normal arteries was considerably poorer in the CW Doppler study than in our present results. CW Doppler detects all particles moving across the vessel, and consequently variation in the distribution of flow velocities will occur (Figure 1, top). In contrast, the small sample volume used in the pulsed-wave Doppler technique allows true flow disturbances to be differentiated from the effect of laminar flow with a blunt profile.

In our present study we used the flow profile merely to secure the correct positioning of the sample volume. It might be possible, however, to see disturbed flow directly on the profile. The obvious difference between the two profiles seen in Figures 1 and 7 is suggestive. The latter was obtained from an ICA just distal to a 65% stenosis. The new color-coded Doppler systems, based on the multigated Doppler principle, might enlighten this interesting question further.

Our improved results in the present study point toward the use of pulsed-wave Doppler systems to discriminate between normal arteries and vessels with only minor changes. In our routine examination we combine the CW and pulsed-wave multigated Doppler techniques. First the vessel is examined using CW Doppler, and if a stenosis is disclosed no further Doppler examinations are performed. If the CW Doppler examination is within the normal range,2 we routinely perform pulsed-wave multigated Doppler examination as described.

TABLE 3. Using Spectral Broadening Indexes of 0.20 and 0.37 for Pulsed-Wave Multigated Doppler Ultrasonography to Classify Stenosis: Correlation With Arteriography

<table>
<thead>
<tr>
<th>Doppler ultrasonography</th>
<th>Arteriography</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>1–49%</td>
</tr>
<tr>
<td></td>
<td>50–99%</td>
</tr>
<tr>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>0%</td>
<td>19</td>
</tr>
<tr>
<td>&lt;50%</td>
<td>2</td>
</tr>
<tr>
<td>≥50%</td>
<td>0</td>
</tr>
<tr>
<td>100%</td>
<td>0</td>
</tr>
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References


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