DOPPLER SONOGRAPHY has become an accepted method for clinical detection and evaluation of cervical carotid occlusive disease. One of the most important parameters used in Doppler assessment of carotid stenosis is the peak Doppler shift frequency occurring during systole.* Relatively little data is available, however, to indicate how precisely peak systolic frequency correlates with luminal narrowing and how peak systolic frequency measurements made with frequency spectrum analysis should be used in clinically gauging stenotic lesions.

Spencer and Reid,1 using a 5 MHz continuous wave Doppler, compared peak frequencies in normal and stenosed internal carotids with those predicted by a theoretical model. The formulation of practical suggestions for using peak frequency in predicting severity of stenosis was beyond the scope of their work; nonetheless, the wide variation evident in their data suggests that precise assessment of stenosis is not possible with peak Doppler frequencies.

The objectives of our study were to further investigate the relationship of peak frequency and carotid stenosis and, in particular, to develop practical suggestions for the use of peak frequency in clinical evaluation of cervical carotid occlusive disease.

**Materials and Methods**

Seventy-five cervical carotid stenoses were identified in which the degree of lumen narrowing could be accurately measured from carotid arteriograms and in which good quality spectral analysis could be obtained from recorded Doppler signals. Fifty-eight of these stenoses were located in the internal, 12 were in the external and 6 were in the common carotid artery. Calipers were used to measure the lumen diameter in the stenotic and non-stenotic zones on AP and lateral selective carotid arteriograms (fig. 1A). The arteriograms were measured blindly by two independent observers. If the measurements disagreed by more than 0.5 mm, the films were remeasured by a third independent observer in an effort to form a consensus. Cases were discarded from the study if agreement could not be established by two observers or if accurate measurement could not be accomplished in two projections (table 1).

The ratio of the diameter of the stenotic zone to the diameter of the normal vessel was used to calculate the percent reduction of area in each radiographic projection (fig. 1B). In the case of carotid bulb lesions, the diameter of the common carotid was used as the measurement of the normal portion of the vessel. This was felt to be logical since we were concerned in this study with flow restriction. It is recognized, however, that the normal diameter of the bulb exceeds that of the remainder of the common carotid in many cases. The same approach for measurement was used in the internal carotid, recognizing that the orifice of this vessel is also frequently larger in diameter than the remainder of the vessel. If the measurement of percent decrease in area in the two projections fell within 10%, the two values were averaged. If the difference between the measurements was greater than 10%, the lumen of the stenotic zone was considered to be elliptical, and the percent decrease in area was calculated using a formula which relates the area of an elliptical lumen to the area of the normal portion of the vessel (fig. 1C). Peak Doppler-shifted frequency was measured from frequency spectra produced either with a Kay Sonograph Model 7030* or a SONOCOLOR 6000** (fig. 2). Cases were excluded from the study if adequate sonographic data was unobtainable due to technical factors (table 1).

All frequency data was obtained retrospectively from carotid Doppler examinations performed in our Department during the past four years using a 5 MHz, continuous-wave, directional Doppler bloodflow de-

SUMMARY The peak Doppler-shifted frequency and degree of lumen narrowing were compared in 75 cervical carotid stenoses. Peak frequency was not found to precisely indicate severity of stenosis, but it was possible to divide stenoses into four ranges of severity on the basis of peak frequency. Peak frequencies of less than 5 KHz, in most instances, indicated stenoses of less than 50% decrease in lumen area. Frequencies from 5 to 8 KHz were generally associated with stenoses of 50–75% decrease in lumen area, and frequencies of 8–12 KHz were most often associated with stenoses of 75–90% decrease in area. Frequencies greater than 12 KHz almost invariably occurred in very severe lesions of greater than 90% decrease in lumen area (>70% decrease in diameter). The use of peak frequency as an indicator of severity of stenosis, while not specific, is felt to be of considerable clinical benefit as it provides a more quantitative evaluation of stenosis than auditory assessment of Doppler frequencies.
FIGURE 1: Methods for measuring and calculating the percent decrease of lumen area in carotid stenosis. (A) The smallest diameter in the stenotic zone (a) and the normal zone (b) were measured with calipers in the AP and lateral projections (lateral not shown). The diameters of the stenotic and normal regions were entered into the formula shown (B) to calculate percent reduction in area. This calculation was made independently for both the AP and lateral projections. If the calculated percent reduction in area for the AP and lateral projection fell within 10%, the values were average. If the percent reduction in area estimated for the AP and lateral projections varied by more than 10%, the lumen was considered elliptical, and the formula shown (C) was used to calculate percent reduction in area.

\[
\text{% Decrease in Area} = \left(1.0 - \frac{\text{Stenotic Diameter}^2}{\text{Normal Diameter}^2}\right) \times 100
\]

\[
\text{% Decrease in Area} = \left(1.0 - \frac{\text{Stenotic Diameter AP}}{\text{Normal Diameter AP}} \times \frac{\text{Stenotic Diameter LAT}}{\text{Normal Diameter LAT}}\right) \times 100
\]

The patients were examined in a supine position with the neck extended. The Doppler transducer was applied to the neck at a 60° angle from the body axis, and a water-soluble couplant was employed. A position-sensing arm was used to link the position of the transducer to the XY axis of a storage oscilloscope. The oscilloscope beam was activated each time the transducer was moved across the carotid artery, and a crude, two-dimensional image of the carotid bifurcation was produced through repeated passes of the transducer (fig. 3). This image served as a “map” for localization of Doppler signal abnormalities. The Doppler signals in the common, external, and internal carotid were recorded on chromium dioxide magnetic tape with Dolby noise reduction using an Advent**** Tapedeck Model 201. The maximum frequency response level of the entire system was limited to 1600 KHz by the audio tape recorder, and in some cases by the SONOCOLOR 6000 which had an upper frequency limit of 12 KHz.

Results

The stenoses were evenly distributed over a range of 21 to 99% decrease in lumen area. The length of the stenoses varied from 3 to 15 mm. Peak Doppler-shifted frequencies (systolic) in the stenotic zone ranged from 1 KHz to 16 KHz. The relationship of peak Doppler frequency and percent decrease in lumen area is

***Prototype of DOPSCAN®, Carolina Medical Electronics, Inc., King, NC.

****Trademark Advent Manufacturing Corp., Cambridge, MA.
Table 1: Causes for Exclusion of Stenotic Lesions From Study

<table>
<thead>
<tr>
<th>Causes for exclusion</th>
<th>Number of stenosis</th>
<th>% decrease in area</th>
</tr>
</thead>
<tbody>
<tr>
<td>A—Failure to accurately measure stenosis from arteriograms</td>
<td>3</td>
<td>—</td>
</tr>
<tr>
<td>B—Failure to obtain accurate sonographic data</td>
<td>10</td>
<td>—</td>
</tr>
<tr>
<td>Peak frequency bypassed due to poor technique</td>
<td>2</td>
<td>83, 92</td>
</tr>
<tr>
<td>Signals in stenotic area obscured by plaque (large non-sounding area)</td>
<td>1</td>
<td>90</td>
</tr>
<tr>
<td>Stenoses outside of the anatomic range of the instrument</td>
<td>2</td>
<td>75, 96</td>
</tr>
<tr>
<td>Peak frequency obscured by arterial wall pulsation (thumping)</td>
<td>1</td>
<td>76</td>
</tr>
<tr>
<td>Signals too weak for sonographic analysis in a patient with a muscular “thick” neck</td>
<td>1</td>
<td>80</td>
</tr>
<tr>
<td>Tape damaged</td>
<td>1</td>
<td>60</td>
</tr>
<tr>
<td>Signals in one branch of vessel obscured by very strong signals from a severe stenosis</td>
<td>2</td>
<td>51, 65</td>
</tr>
</tbody>
</table>

Graphically illustrated in figure 4. Peak frequencies observed in minor stenoses fit the theoretical model of Spencer and Reid1 fairly closely (fig. 5), but peak frequencies associated with severe stenoses were significantly lower than those predicted in the model. Our data thus resembles the clinical data reported by Spencer and Reid who postulated that the latter finding is most likely due to the effects of collateral circulation which reduces the pressure gradient across a stenosis and thereby lowers flow velocity in the stenotic zone.1

The relatively wide spread of our data points clearly indicated that precise estimation of severity of stenosis was not achieved through measurement of peak frequency. Nonetheless, the distribution of points suggested that severity of stenosis could be approximated by including each lesion in one of four frequency ranges (table 2). Frequencies of less than 5 KHz were found in most cases to indicate minor stenoses in which lumen area was decreased by less than 50% (= 30% decrease in diameter). Frequencies greater than 5 but less than 8 KHz were most often associated with stenoses of from 50 to 75% decrease in lumen area (= 30 to 50% decrease diameter). These lesions might be considered moderately severe but not hemodynamically significant.* Frequencies greater than 8 KHz but less than 12 KHz generally represented severe stenoses between 75 and 90% decrease in area (= 50 to 70% decrease diameter). This was the least specific frequency range, and some stenoses with frequencies nearer to 8 KHz were within the 50 to 75% (area) category. Most stenoses in the 8–12 KHz range may, nonetheless, be regarded as severe lesions potentially of critical hemodynamic significance. Frequencies of 12 KHz and greater were almost exclusively associated with very severe stenoses of greater than 90% decrease in lumen area (70% decrease in diameter) which should be regarded as critical in terms of hemodynamic effects.

A 4 × 4 contingency table (table 3) was established to verify the significance of this grouping of peak frequencies. The results of this evaluation were satisfactory with a Kappa coefficient of .69 for the overall

*The work of Spencer2 indicates that some volume flow and pressure reduction occurs distal to stenoses of 50% or greater decrease in diameter, but that reduction in the flow and pressure does not reach a critical or clinically significant level in carotid disease until the lumen narrowing approaches 70% decrease in diameter.

Figure 2: Method of measuring peak Doppler-shifted frequency from a carotid sonogram. The point of maximum frequency shift (arrow) in this normal case is 3 KHz.
results (standard error .067) and .758 (standard error .052) if the five nearly occluded lesions with reduced flow (table 3) were excluded. A Kappa coefficient of 1.0 indicates perfect association; 0 indicates no association.3

Discussion

In Doppler sonography, the severity of carotid stenosis is estimated on the basis of three principal Doppler signal abnormalities: 1) increase in peak systolic frequency (flow velocity); 2) the presence and severity of post-stenotic turbulence; and 3) increase in diastolic frequencies (flow velocities). These signal characteristics are routinely assessed with the human ear which is rather accurate with adequate training,4,5 but is limited because of subjectivity. In particular, we have noted that increase in loudness of a signal may be confused with increase in pitch; also, it is particularly difficult to estimate the severity of minimal and moderate stenoses with auditory evaluation. Perhaps the greatest disadvantage of auditory interpretation of Doppler signals is that an extended learning period is required during which errors of over and underestimation are likely.6

Less subjective and more precise Doppler methods for estimating the severity of lumen narrowing are desirable. To this end, measurement of peak Doppler frequencies with on-line spectral analysis7,8 and color coding of carotid Doppler images based on peak frequency shifts9,10 have been advocated. The data from this study support the use of these techniques for enhancing the accuracy of Doppler diagnosis even though precise estimation of lumen narrowing does not appear to be possible through measurement of peak systole frequency.

Objective separation of stenoses into the proposed four groups (table 2) is potentially of great value in a screening modality. Inexperienced Doppler sonologists may in particular find this classification system helpful, and our observations suggest that even among seasoned Doppler sonologists, classification of stenoses into four groups is useful. In particular, we feel that use of the four frequency ranges has allowed us to more precisely grade stenoses at all levels of severity and has helped us to avoid errors of over and underestimation. Even experienced Doppler sonologists in our laboratory (including the M.D. authors of this paper) are now reluctant to interpret a study in the absence of adequate spectral documentation.

A Note of Caution

The lack of precision in measuring stenoses with peak frequency which is evident in this data must be emphasized, and it should be recalled that the severity of stenotic lesions should never be determined solely on the basis of one Doppler parameter such as peak
frequency. The other Doppler abnormalities observed in the stenotic vessel which have already been mentioned, and findings such as the presence or absence of external carotid collateral flow and abnormal common carotid resistivity must also be weighed in forming a conclusion. Recognition of the inherent lack of precision in estimating stenosis with peak frequency appears especially important in the 8–12 KHz range where the widest spread of our data occurred.

In addition to these precautions, awareness of the particular difficulties associated with Doppler evaluation of very severe stenoses is important. In such lesions, marked reduction of blood flow may be associated with peak frequencies much lower than expected. Five such cases are evident in this study (fig. 4). In four of these, Doppler frequencies were less than 5 KHz even though lumen area was reduced by more than 95%.

Some authors recommend the use of carotid sonography as part of a battery of noninvasive tests including such procedures as oculoplethysmography or carotid phonoangiography. Our previously published data, based solely on the use of continuous-wave Doppler carotid imaging techniques and ophthalmic flow assessment demonstrate an overall accuracy rate of 95% for detecting the presence or absence of lesions greater than 70% decrease in diameter or complete occlusion. Preliminary data on combined continuous-wave and B-mode examination of 32 cervical carotid occlusive lesions in 36 bifurcations gathered in our laboratory demonstrate a 78% overall accuracy rate for estimating severity of occlusive lesions grouped into four categories (<50%, ≥50%, <70%, ≥70% decrease diameter, and complete occlusion). In assessment of the presence or absence of lesions of greater than 70% decrease diameter or complete occlusion, we were 92% sensitive, 96% specific, and 95% accurate overall in this series. On the basis of these figures, we have not felt a need to employ procedures other than Doppler and high resolution B-mode ultrasound for carotid screening.

Finally, it must be emphasized that the results of this work apply to a specific type of Doppler instrument. Other Doppler devices including pulsed and duplex equipment may be more or less accurate in correlation of peak frequency and stenosis according to limitations.
imposed by design of the instruments, as well as by methods of examination. Furthermore, the frequency ranges corresponding to specific degrees of stenosis will differ from those reported herein if the incident Doppler frequency is other than 5 MHz.

**Causes for Lack of Precise Correlation of Peak Systolic Frequency and Stenosis**

The absence of precise correlation between peak frequency and percent decrease in lumen area demonstrated in this study may be attributed to numerous factors, but two reasons appear to be particularly important. First, it is widely accepted that arteriosclerotic plaque develops asymmetrically within carotid vessels and that this asymmetry of lumen narrowing results in inaccuracy when the severity of stenosis is estimated from arteriograms. We have attempted to minimize error in measuring the residual lumen area by treating obviously asymmetric lesions as ellipses rather than circles. Nonetheless, the limited number of projections available angiographically cannot be expected to accurately describe the dimensions of a stenotic vessel. Added to this problem is lack of precision in measuring the lumen diameter from angiograms. We found that our measurements were repeatable within a range of only 0.5 mm.

The following factors are also felt to contribute to the observed lack of precision in our data: 1) Resistance to blood flow increases in direct proportion to the length of the stenotic lesion, hence, a longer stenosis can be expected to have a lower flow velocity and peak frequency than a short stenosis of the same degree of luminal narrowing. 2) In many stenoses, especially those which are severe but are short in length, the zone of high velocity flow may be localized to a very small volume. It may be difficult or impossible under clinical circumstances to position the sound beam with sufficient accuracy to detect the region of maximum velocity, and the peak Doppler shift may, therefore, be underestimated. 3) The orientation of the transducer relative to the stenotic lumen may vary greatly from patient to patient depending on the course of the vessel within the neck and the location of arteriosclerotic plaque within the vessel lumen. Resulting alterations in the vector of flow relative to the transducer may cause over or underestimation of peak frequency shifts. 4) Turbulence in and adjacent to the stenotic zone may also affect the observed vector of flow relative to the transducer and cause spurious elevation of peak frequencies. Alternately, strong turbulent flow in or near the stenotic area may obscure weak high frequency signals arising in the stenotic lumen and cause errors of underestimation. 5) Inadvertent compression of the carotid vessels caused by pressure on the transducer may accentuate lumen narrowing and exaggerate the peak frequency shift. 6) Hypertension, decreased arterial compliance, and tachycardia may increase flow in the stenotic zone and cause spurious elevation of peak frequency. 7) Likewise, bradycardia may reduce peak frequency below that which would normally occur at a specific level of stenosis.

**Conclusion**

Correlation of peak Doppler-shifted frequency and percent decrease in lumen area in 75 stenotic lesions suggests that peak Doppler-shifted frequencies observed in a clinical setting do not provide precise information concerning severity of carotid stenosis. Nonetheless, stenotic lesions can be grouped into four categories on the basis of peak frequency, and these categories may have considerable clinical utility.

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