SUMMARY The value of the concomittant use of a real time frequency analyzer along with a continuous wave carotid Doppler scanner is demonstrated in this study of 118 cases. With a colour-coded Doppler scanner alone, internal carotid stenoses greater than 35% were diagnosed with a sensitivity of 95% and a specificity of 82%. With the addition of frequency analysis certain inherent problems with Doppler scanning were overcome and with the measurement of the peak Doppler frequency, the specificity was improved to 93%.

NONINVASIVE TECHNIQUES for diagnosing extracranial carotid disease are becoming more important as an adjunct in the management of patients with cervical bruises or atypical neurological symptoms. Of the alternative noninvasive methods, carotid Doppler scanning1 has become quite popular because it is a direct method and records the flow velocity changes which occur in the carotid artery at the site of the stenosis, rather than measuring the indirect changes in pressure, flow, or pulse wave velocity at distal sites that are recorded by the indirect methods such as periorbital Doppler2 and oculoplethysmography.3, 4

With most of the early Doppler scanners, an image of the carotid bifurcation was produced using continuous wave or pulsed Doppler ultrasound and the technician confirmed the presence of a stenosis by listening to the audio signal and noting that high frequency sounds were present. Several advances have been made in Doppler imaging one of which was the introduction of the Echoflow® colour-coded scanner which superimposed three colours on the scan to indicate if the Doppler frequencies were normal, moderately increased, or significantly increased. In spite of significant technical improvements, we found that Doppler scanners have the following limitations:5 subjective interpretation of the audio signal was not always a reliable way to confirm the presence of a stenosis; although the colour-coded scanner was more objective, with the use of only three colours to record the peak frequency, the results were occasionally ambiguous; when mild to moderate stenoses were present there was no way to confirm if the increased frequencies were abnormal and indicative of a stenosis or increased but normal, as may occur in a young individual, or in those cases with contralateral stenoses and a compensatory increase in flow; it was occasionally difficult to distinguish the internal and external carotid arteries and thus to accurately localize the site of the occlusive disease; when the Doppler signal is weak relative to the background electronic noise, as may occur when the vessel is deep or very diseased, the scan results and the subjective analysis of the Doppler sounds was difficult; the diagnosis of internal carotid artery occlusion was difficult to confirm in many cases; and tandem lesions could not always be detected.

In our vascular laboratory, we had an extensive experience with the use of real-time frequency analysis in the study of more than 6,000 patients with peripheral arterial occlusive disease and felt that many of the limitations of carotid Doppler scanners could be overcome by adding a frequency analyzer to the Echoflow Doppler system. Thus, we felt that the colour-coded scan of the carotid bifurcation could be augmented by the interpretation of the individual carotid Doppler waveforms recorded from representative sites on the scan.

The purpose of this paper is to document the advantages of using a real-time frequency analyzer in combination with the Echoflow carotid Doppler scanner for diagnosing extracranial carotid artery disease and show that this improves the diagnostic accuracy.

Methods

The carotid Doppler scans were performed by an experienced vascular laboratory nurse using the Echoflow colour-coded scanner. The scanning arm, containing a 4 MHz continuous wave Doppler probe was positioned over the neck and then moved back and forth over the carotid arteries. The received Doppler signal is adjusted automatically to a constant level, passed through three filters, and the maximum Doppler frequency is determined by a microprocessor program. Based on the measured maximum frequency a red dot is printed on a colour video screen at the appropriate XY coordinate if the frequencies fall within the range 0.8 to 2.6 KHz, yellow if the peak frequency is approximately 3.6 KHz, and blue if approximately a 5 KHz frequency is present. No colour is produced if the artery is occluded and no Doppler signal is received. The scans were considered abnormal and indicative of the presence of a hemodynamically significant stenosis if a persistent yellow or blue colour was present at more than one point, and all the way across the scan of the common carotid or internal carotid arteries or if the internal carotid artery was shown to be occluded.

A real-time frequency analyzer of our own design6
was connected to the audio output of the Echoflow Doppler and simultaneously processed and displayed the same Doppler signals which were used to produce the colour coded scan. Thus it was possible to examine the Doppler spectral waveforms at each of the individual colour points recorded on the Doppler scan.

One hundred and eighteen consecutive biplane arteriograms were evaluated without knowledge of the scan results.

A micrometer was used to measure the minimum residual lumen diameter at the site of the stenosis (or the internal carotid bulb 0.5 cm above the bifurcation if no stenosis was present) and the diameter of the distal extracranial internal carotid artery. The percentage internal carotid diameter stenosis was calculated.

**Results**

In this section, we will describe the accuracy of results obtained by using the Echoflow carotid Doppler scanner together with a real-time frequency analyzer and in the following section will discuss how the frequency analyzer can augment the Doppler scanning technique and overcome some of its limitations.

The Echoflow carotid Doppler scanner and a real-time frequency analyzer were used simultaneously in more than 400 carotid Doppler studies. One hundred eighteen consecutive biplane arteriograms were available for study. It should be noted that the final colours recorded on the scans were used for interpretation of the results, but during the examination the technician used the information from the frequency analyzer to determine if artifacts were present due to electronic errors or for physiological reasons. Additional measurements from the Doppler spectral waveforms, such as peak frequency, peak frequency ratios, or spectral broadening were not used to determine the results reported in this study.

In figure 1, the relationship between the colour recorded on the scan is plotted against the percentage internal carotid diameter stenosis. When all 118 vessels are included (i.e. 109 arteries with stenoses greater than 35% internal carotid diameter stenosis and 9 occlusions) the sensitivity of the method was 96% and the specificity 80%. As discussed below, for the most part, the serious errors were probably technical and the result of incorrectly identifying the complete occlusion or reporting a stenotic vessel as occluded. However, the lower than expected specificity may also, in part, be attributed to the overlap which results from using only three colour threshold levels. This overlap is illustrated in figure 2 where the maximum consistent colours recorded by the Echoflow system are plotted against the maximum frequency recorded at the same time by the frequency analyzer. The average frequency (± 1 standard deviation) for each of the colours follows: red = 2.4 ± 0.6; yellow = 3.9 ± 1.1; and blue = 7.4 ± 2.8 KHz.

**Discussion**

In the following sections, we illustrate the advantages of using a frequency analyzer along with a carotid Doppler scanner and show how it overcomes some of the problems described above.

**Confirm the Presence of the Stenosis**

Our experience confirms the observations of other workers that analysis of the Doppler spectral waveforms recorded by the frequency analyzer confirms if a stenosis is present. A normal internal carotid recording is illustrated in figure 3A. The maximum frequency is quite low (1.0 to 3.5 KHz with a 4 MHz Doppler probe) and there is a clear window present under the systolic peak indicating that laminar flow is present and that the velocity profile is quite flat. At the site of an internal carotid stenosis (fig. 3B), the peak frequency is increased and the window is obliterated because the flow is disturbed. Further, when a yellow colour is displayed on the Echoflow Doppler scan, the frequency recordings are of value in determining if the increased velocity is normal or abnormal. For example, the peak velocity may be increased but the Doppler recordings are otherwise normal in normal subjects if the carotid artery is tortuous, if the patient's circulation is hyperkinetic, or if significant occlusive disease is present in the contralateral carotid artery. By comparing...
son, if the peak velocity is increased as the result of an arterial stenosis, the Doppler recordings will show evidence of disturbed blood flow with obliteration of the window under the systolic peak.

Confirm the Severity of a Stenosis

As illustrated in figure 4, the peak carotid Doppler frequency measured by the frequency analyzer can be used to determine the severity of the arterial stenosis, and appears to be more accurate than using only three arbitrary threshold levels. For the same 118 cases, we found that a peak frequency greater than 3.8 KHz was diagnostic of a stenosis greater than 35% of the internal carotid diameter with a sensitivity of 92% and a specificity of 93%. The improved specificity is achieved by reducing the overlap which occurs between the red and yellow filters of the Echoflow system.

Confirm the Site of Stenosis

The anatomical relationship between the internal and external carotid arteries is quite variable. For example, the two vessels may lie over one another and/or be tortuous. As a result, in a specific scan the exact site of the stenosis may be difficult to determine. In figure 5, the spectral recordings clearly show that there is a severe stenosis involving the external carotid artery only and that the internal and common carotid arteries are normal. In this case the scan demonstrated an area of increased velocity, but the exact site was ambiguous since the origins of the internal and external carotids were superimposed and it was unclear if the stenosis involved the internal or the external carotids, or both.

Detect Low Velocity Signals Distal to a Severe Stenosis

If a hemodynamically significant stenosis is present in the proximal common carotid artery or aortic arch, the peak velocity is reduced distally. If the velocity of flow is very low the Doppler scanning system may not produce a carotid image since the signal may be below the threshold level for detection. However, a frequency analyzer with a manual gain control can usually be adjusted to display the severely dampened waveforms and at least allow the operator to determine if the distal artery is patent and to evaluate the signals subjectively.

A similar problem occurs if a very severe internal carotid stenosis is present. The blood flow velocity in the distal internal carotid may be so low that the scan-

**Figure 3.** Carotid Doppler frequency analysis recordings. (A) Normal internal carotid recording and (B) recording at the site of severe stenoses.

**Figure 4.** The relationship between the peak Doppler frequency recorded by the frequency analyzer and the percentage internal carotid diameter stenosis. Note that in the cases with minimal or no stenosis, the diameter of the bulb may be larger than that of the internal carotid and hence the calculated percentage stenosis of the distal internal carotid may be negative.
Diagnose Tandem Stenoses

A frequency analyzer will help determine if two stenoses are present in tandem. For example, in figure 6, the left common carotid recording is dampened because of a severe proximal common carotid stenosis. A second bifurcation stenosis raised the peak frequency to 7.4 KHz. On the right side, the common carotid recording is normal and an internal carotid stenosis of similar severity increased the peak frequency to 11.8 KHz. In this situation, the potential error of the colour-coded scanner, with only three arbitrary frequency ranges, can be appreciated by considering a 50% area stenosis. If the common carotid velocity is normal, the internal carotid will increase twofold and trigger the yellow or blue filters. By comparison, if the common carotid velocity is significantly reduced by a proximal lesion, the same 50% stenosis will increase the frequency over the stenosis twofold but only the red or yellow colour will be displayed and will not reflect the severity of the stenosis. From frequency analysis recordings, the severity of the area stenosis (% AS) can be determined from the equation: % AS = (1 - F1/F2) x 100, where F1 = peak Doppler frequency recorded proximal to the stenosis and F2 = peak frequency recorded over the stenosis.

Evaluate Flow Pattern When the Doppler Signals are Attenuated by a Plaque

An atherosclerotic plaque at the carotid bifurcation may attenuate the Doppler signal so severely that images are not recorded by a Doppler scanner. Although the operator can often suspect the presence of a signifi-
significant plaque by noting that the Doppler signals sound "very distant," the frequency analyzer recordings are more helpful since they record irregular poor quality signals which are produced only after the manual gain control is adjusted to quite high levels. Even with poor quality recordings, it may be possible to determine if a severe stenosis is present.

Distinguish External and Internal Carotid Artery

With a Doppler scanner, the technician usually distinguishes between the internal and external carotid arteries on the basis of their locations and the difference in their audio sounds. This is usually straightforward in normal subjects but in patients with stenoses may be very difficult. Especially in this latter group of
patients the distinction is easier if a frequency analyzer (fig. 7) is used to provide visual feedback to the technician in addition to the audio feedback.

**Substantiate Diagnosis of Internal Carotid Occlusion**

Following internal carotid occlusion, the branches of the external carotid may dilate and become very tortuous. It is possible to scan two branches of the external carotid and incorrectly label them as the internal and external carotids. However, careful examination of the spectral recordings will usually show that the branches are, in fact, both from the same system.

Frequently it is possible to confirm the presence of internal carotid occlusion by examining the common carotid Doppler spectral waveforms. Normally, when the internal carotid is patent, the peripheral resistance is quite low and the diastolic flow is quite high. On the other hand, following internal carotid occlusion, the peripheral resistance is increased and the common carotid waveform resembles that seen in the external carotid (fig. 8). Unfortunately, in long-standing internal carotid occlusions, if large collaterals form between the external carotid and the intracranial vessels, the resistance to flow in the external carotid may become quite low and the external carotid waveform may resemble that seen in the internal carotid.

**Distinguish Between Arterial and Venous Flow Signals**

Arterial and venous flow can usually be distinguished by their distinct sound patterns and/or the direction of flow recorded by the Doppler meter. However, as illustrated in figure 9, especially when venous flow is particularly pulsatile, frequency analysis recordings are very useful.

**Conclusions**

Carotid stenosis can be diagnosed noninvasively using a carotid Doppler scanner. This study describes certain problems and limitations of this method and illustrates how many of these difficulties can be overcome by concomitantly using a real-time frequency analyzer with the scanner. In 118 cases, internal carotid stenoses greater than 35% were diagnosed from the results of the colour-coded Doppler scans alone with a sensitivity of 95% and a specificity of 82%. With the addition of frequency analysis and the measurement of the peak Doppler frequency, rather than relying on three arbitrary colour levels, the specificity was improved to 93%. In this study, we used the Echoflow system; however, the limitations described above apply equally to other scanning systems. The results obtained with continuous wave scanners should be im-

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**Figure 8.** Common carotid (COM) resembles the external carotid (EXT) because the internal carotid is occluded.

**Figure 9.** Normal carotid recording with superimposed pulsatile venous flow.
proved by the concomitant use of real-time frequency analysis.

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References

Carotid Physiology with Ocular Pneumoplethysmography
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SUMMARY The ocular pneumoplethysmograph (OPG-Gee) defines both the qualitative and quantitative physiology of the carotid arterial hemisystems and associated hemodynamically significant lesions. This report defines this physiology in 667 patients, all of whom underwent arteriography.

PREVIOUS REPORTS on the clinical application of the ocular pneumoplethysmograph (OPG-Gee) have emphasized the screening aspect of this instrument in the detection of hemodynamically significant carotid lesions.1,2 These reports were based on data obtained between 1973 and 1978, during which time the maximum vacuum capacity of the instrument was 300 mm Hg. Early in 1978 the instrument was modified to allow a maximum vacuum capacity of 500 mm Hg. The data derived with the latter instrument have substantially improved its accuracy as a screening device. However, an aspect of the instrument not previously emphasized is its ability to characterize the physiology of hemodynamically significant carotid lesions and the intracranial consequences of the various combinations of these lesions, as they are encountered clinically in the individual patient. This report describes this physiology in 667 patients, all of whom underwent arteriography.

Methods
Although a number of factors contribute to the hemodynamic significance of a carotid lesion, the principal element is the relationship between the cross-sectional area of the residual lumen at the level of the lesion and the cross-sectional area of the normal artery distal to the carotid bulb. Arteriography defines the lumen diameter at these two levels, but if the same diameters are noted in two planes at right angles to each other, cross-sectional areas can be calculated. Experimental work has defined a 75% cross-sectional area stenosis as pressure-significant and a 90% cross-sectional area stenosis as flow-reducing or critical.3

Figure 1 is a diagrammatic representation of these two stenoses as seen in the typical location in the internal carotid artery. Although only one plane is demonstrated in each instance, cross-sections of both define the stenoses as circumferential.

The standard procedure for the OPG study is as follows. With the patient in the sitting position, both brachial blood pressures are determined by arm cuff and auscultation. This is a very important step, as any substantial difference in these measurements is indicative of considerable arterial stenosis on the side of the lower pressure. With the patient in the supine position, the OPG test is done as previously described.4 Immediately upon completion of the test, with the patient remaining in the supine position, the brachial blood pressure is again measured in the standard fashion. This determination is made in the arm with the higher pressure noted in the sitting position. The bilateral ophthalmic systolic pressures (OSP) as determined by the OPG are then plotted against the brachial systolic pressure (BSP) measured immediately after the OPG test. The BSP is plotted on the x-axis (abscissa) of a graph, and the OSP is plotted on the y-axis (ordinate). The resulting point is termed a (BSP,OSP) coordinate. The derivation of the criteria are:
Problems of carotid Doppler scanning which can be overcome by using frequency analysis.
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