Quantitation of Carotid Stenosis with Continuous-Wave (C-W) Doppler Ultrasound

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SUMMARY Two methods for determining the degree of stenoses developing on the origin of the internal carotid were tested using non-invasive Doppler ultrasonic imaging (DOPSCAN) of the carotid bifurcations. Spectral analysis of Doppler audio recordings was utilized in determining the maximum frequencies found within the stenosis, as well as the ratio of the frequency downstream to the stenosis, to the frequency within the stenosis. The theoretical relationships between blood flow, velocity, and pressure drop are defined for all grades of stenosis and they predict that carotid flow will not be reduced unless the lumen diameter is less than 1.5 mm. At critical diameter reductions, below 1 mm, the frequencies in human carotids do not exceed 16 KHz because turbulence limits peak velocities. If the maximum systolic frequency exceeds 5 KHz, when 5 MHz probes are directed at a 30° angle from the body axis, there is always present stenosis up to diameters of less than 3.5 mm by x-ray angiographic measurements. Frequency ratio studies confirm that plaque growth is not symmetrical but they did not improve x-ray angiography correlations because of the limitations of x-ray in measuring cross sectional areas from projection films and limitations of the spot size of x-ray tubes.

Methods

Carotid blood velocity was measured with 5 MHz continuous-wave (C-W) directional Doppler ultrasonic equipment designed and built in the Bioengineering Center of this Institute. The ultrasonic probe consists of a dual-crystal lens-focusing transducer mounted on a position sensing arm and directed toward the carotid arteries at a 60° angle from the body axis. With this equipment and procedure, a 1 KHz Doppler frequency shift represents a blood velocity of 30 cm/sec. The probe is placed against the neck with intervening coupling jelly and the Doppler shifted frequencies are recorded. A Doppler image of the carotid bifurcation (DOPSCAN), including the common carotid and its external and internal

THE ADVERSE CLINICAL EFFECTS of atherosclerotic plaques on the carotid artery are manifest in the patient’s eye and brain through reduction of blood perfusion following stenosis of the channel or by embolization from the site of the plaque. It is generally agreed that more than one-third of strokes result from cervical arterial disease and primarily from plaques occurring on the origin of the internal carotid artery. For stroke prevention the identification of carotid plaques and quantitation of stenosis is of primary importance.

Non-invasive diagnostic methods are needed to evaluate patients with symptoms of cerebrovascular insufficiency because of the inherent dangers and costs of the alternative, x-ray contrast angiography. In addition, they are needed for medical or surgical follow up in the study of the natural history of the atherosclerotic plaque. With the general availability of non-invasive Doppler ultrasound, which provides blood velocity signals from the carotid arteries, it is important to fully utilize this information to evaluate the degree of stenosis and the attendant collateral circulation. This paper presents a system for determining the degree of stenosis using the increased Doppler audio frequencies within the stenotic segment.

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*Obtainable from Carolina Medical Electronics, King, North Carolina.
branches, is developed. Magnetic tape recordings are made of selected audio signals for later spectral analysis. Diameters calculated from Doppler findings were compared with the minimal diameter measurements found on x-ray contrast angiographic films.

Three methods were tested to determine the lumen cross section at the origin of the internal carotid artery. All methods used spectral analysis of Doppler signals to determine the maximum systolic frequency \( f_{\text{max}} \), (fig. 1). Though the mean frequency \( f_\text{m} \) is preferable because it represents the mean velocity \( v \), \( f_{\text{max}} \) is substituted because it can be more accurately determined than \( f_\text{m} \) which must be derived from the zero crossing meter. Though zero crossing meters are available, their accuracy in determining \( f_\text{m} \) is questionable.

The first method tried, and the simplest to perform, utilized only the greatest frequency found at the site of the stenosis, \( f_{\text{max}} \). The other 2 methods utilized the frequency ratio between the internal carotid signals found at the angle of the jaw, \( f_{\text{max}} \), downstream to the origin, and \( f_{\text{max}} \), (fig. 2).

The theoretical basis for our first method was the concept that a decreasing cross sectional area within a stenotic segment would produce an increase in velocities and corresponding Doppler shifted frequencies. Theoretical model predictions were carried out to determine the maximum range of Doppler frequencies that might be expected with internal carotid stenosis.

Assuming a linear relationship between resistance \( R \) and blood flow \( F \), \( R \) was calculated in dynes-cm.sec from the following equation:

\[
R_{\text{dy. cm. sec}} = \frac{8\eta L}{\pi r^4}
\]

Where \( \eta \) represents the viscosity of the blood (nominal value of 0.04 Poise), \( L \) represents the length of the stenotic segment (nominal value of 0.2 cm) and \( r \) represents artery radius. \( R \) is converted to clinical terms of mm Hg/ml/min by dividing by 79,380, and flow for any given stenosis was calculated from:

\[
F = \frac{\Delta P}{R}
\]

The mean velocity \( \langle v \rangle \) was calculated from the following equation:

\[
\langle v \rangle = \frac{F}{60 \pi r^4}
\]

The calculations considered a network model (fig. 3) in which the origin of the internal carotid artery was represented by a linear resistance \( R_1 \). We also compared both the relationship of the ratio \( f_{\text{m}}/f_\text{m} \) and the \( \sqrt{f_{\text{m}}/f_\text{m}} \) to the minimum x-ray diameter using the principle of continuity of flow in the unbranching internal carotid artery (fig. 4). The rationale for using \( f_{\text{m}}/f_\text{m} \) without a square root function, is based on the concept of plaque development on one side of the artery lumen and growing across the artery lumen. The differences expected from symmetric and asymmetric stenosis are illustrated in figure 5. In order to test which of these assumptions was most correct the x-ray angiographic diameter at the origin of the internal carotid was compared with each frequency ratio method.

X-ray contrast angiographic films were analyzed and compared with Doppler frequencies from 95 internal carotid arteries from 64 patients, representing all usable studies by both methods in 2 Seattle vascular laboratories during one calendar year. The minimum diameter found at the origin of the internal carotid was measured with a micrometer utilizing all available films. If no stenosis was present the diameter was measured at a distance of 0.5 cm from the bifurcation to represent \( D_1 \). \( D_2 \) was measured 5–6 cm downstream.

From the best available films the minimum \( D_1 \) could not be measured with certainty within 0.5 mm, and greater uncertainty was often present. The least measureable x-ray diameter was found, using phantom wires, to be 0.8 mm and probably represented the maximum carotid diameter found at the angle of the jaw, \( f_{\text{max}} \), downstream to the origin, and \( f_{\text{max}} \), (fig. 2).

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Model Predictions

Figure 6 represents the theoretical relationships between \( F, \langle v \rangle \), and lumen diameter (D) as well as the expected mean Doppler frequency in KHz. Control flow was set at 300 ml/min, \( P_t \) at 100 mm/Hg and brain resistance \( R_3 \) and resistance of the collateral channels \( R_4 \) were assumed to be equal at 0.333 PRU's. It is apparent, from the model data, that increasing degrees of axisymmetric stenosis will not diminish the blood flow through the artery below 10% of its control value until the diameter within the stenosis is less than 1.5 mm. During this early phase, termed Grade I stenosis, blood velocity and corresponding Doppler frequencies progressively increase in an exponential manner proportional to the inverse square of the diameter. Below a diameter of 1 mm a critical phase is reached when a small decrease in
FIGURE 2. DOPSCAN image of the carotid bifurcation in a patient with a "tight" stenosis of the internal carotid. Frequencies within the stenosis ($f_s$) are elevated while downstream frequencies ($f_d$) are decreased below normal.

FIGURE 3. Resistive model for internal carotid circulation to the brain. Normal flow through $R_1$ is also primarily through $R_4$ with a small amount through $R_3$.

Since: $v_1 A_1 = v_2 A_2$ and $v_1 D_1^2 = v_2 D_2^2$

$D_1 = D_2 \sqrt{f_2 / f_1}$

FIGURE 4. Rationale for calculating arterial stenosis from Doppler signals. $D_1$ represents the diameter at the origin of the internal; $D_2$ represents the downstream diameter; $f_1$ represents the mean Doppler frequency found within the stenotic segment on the origin of the internal carotid; and $f_d$ represents the mean Doppler frequency downstream to the origin.

Lumen diameter produces a great decrease in blood flow. This critical phase is termed Grade III stenosis. In Grade III stenosis, velocity reaches its greatest values but variations in collateral resistance around the stenosis greatly affects $F$ and $V$. In Grades IV and V, velocities decrease again through the frequency range of Grades I and II and flow is greatly diminished to zero at occlusion.

FIGURE 5. The difference in relationship between diameter and cross sectional area for asymmetric and axisymmetric stenosis.

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DOPSCAN FOR CAROTID STENOSIS

Carotid Diameters and Doppler Frequencies

The spectral distribution of frequencies representing blood velocities in the internal carotid arteries of a healthy subject, age 21, are seen in figure 1, where a concentration of energy near the maximum frequency edge \( f_{\text{max}} \) of the spectrum provides the normal "smooth" or "breezy" quality to the audio signal.

Figure 7 illustrates the relationship between \( f_{\text{max}} \) and the x-ray minimal diameter in each of 95 human internal arteries. The horizontal lines represent greater than usual uncertainty of the x-ray measurements. For 77 diameters greater than 1.5 mm, \( D_0 = 8.77 \pm 0.87 \) with a coefficient of correlation of 0.74. The close correspondence of \( f_{\text{max}} \) and \( D_0 \) to the inverse square relationship is apparent. Progressive deviation from the theoretical relationship develops progressively but becomes severe when the diameter decreases below 2 mm. No stenoses less than 0.5 mm were found on the films as predicted from the phantom measurements. The highest Doppler frequencies measured were 15–16 KHz and occurred in the diameter range of 0.75 to 2 mm.

Frequency Ratios

Figure 8 illustrates the first results obtained when we utilized the square root of the frequency ratio \( \sqrt{f_0 f_1} \). In this method, the downstream diameter \( D_0 \) is assumed to be 5 mm because a series of x-ray film measurements determined that this figure represented the median diameter of the internal carotid at the...
The most important problem with x-ray resolvability of stenotic lesions is its inability to represent the cross sectional area of a stenotic segment. Because plaques develop on one side of the artery and expand asymmetrically toward the axis, because the number of x-ray projections are limited and resolvability appears greater than 0.8 mm, the true cross sectional area of the lumen cannot be measured. The Doppler frequency, which is related to velocity, is, however, closely related to the cross sectional area as well as to volumetric flow. The differences between Doppler and x-ray may be expected on the basis of x-ray inaccuracies alone, and the final test of Doppler awaits a better standard for comparison.

Precision in measurement of carotid stenosis is probably only needed for the higher degrees of stenosis where blood velocities are low, resulting in dangers of large thromboembolisms. In this situation, Doppler may find its greatest role in stroke prevention measures. For stenoses greater than 70% (diameter 1.5 mm or less), predicted by a Doppler systolic frequency of 10 KHz or greater, Doppler provides a 63% sensitivity, 85% specificity, and an overall accuracy of 95%.

Discussion

The findings that the Doppler frequency ratio, rather than its square root, provides a better prediction of the least x-ray diameter, confirms the observations of both pathologists and radiographers that plaque development is, in fact, asymmetric. Though figure 5 illustrates the relationship between the cross sectional area and the least diameter in only one type of asymmetric stenosis, many variations in the form of asymmetry produce a similar effect and all differ from the axisymmetric case by lying closer to a linear relation than does the axisymmetric case.

Results using $f_2/f_1$ without the square root function are shown in figure 9. The positive intercept is eliminated leaving only the random variations. A test for closeness of fit to the line of identity gave the figure of 0.70, allowing an accuracy ± 20% in 80% of the cases. For diameter ratios greater than 1.4, where an unusually large bulb occurs at the origin of the internal carotid, a complete loss of correlation occurred. In these situations, of course, stenosis is not present.

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