A Simple, Non-Dimensional, Normalized Common Carotid Doppler Velocity Wave-Form Index That Identifies Patients with Carotid Stenosis

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SUMMARY A non-invasive Doppler velocity index that is specific for carotid artery stenosis is presented. The index is both non-dimensional (maximum/minimum velocity to remove within artery Doppler signal variability) and normalized (larger over smaller carotid maximum/minimum ratio to minimize between patient variability). Of 260 normal patients 94% had a maximum/minimum index between 1.00 and 1.25 and 97.5% had an index between 1.00 and 1.30. In 136 patients undergoing selective carotid arteriography the overall accuracy of the maximum/minimum index in predicting carotid stenosis was 85-87%. When 1.30 is taken as the maximum normal index value the test is 96.5% specific and 76% sensitive. The receiver operating characteristic curve indicates that patients with a maximum/minimum index greater than 1.4 have a 99% probability of significant carotid stenosis.

DOPPLER ULTRASOUND velocity wave-forms have been shown to be abnormal in a variety of peripheral arterial atherosclerotic conditions. Non-dimensional Doppler velocity wave-form indices remove the inherent problems of signal amplitude and probe-to-artery angle in Doppler velocity wave-form analysis. However, there is a considerable variability in Doppler velocity wave-forms between patients with anatomically and physiologically similar common carotid arteries. That is, patients with normal carotid arteries have non-dimensional indices that overlap considerably with patients with carotid stenosis. To remove this between-patient-variability, the non-dimensional index can be normalized. To quantitate differences in common carotid arteries between patients with and without carotid artery stenosis we calculated a non-dimensional normalized Doppler velocity index — the maximum to minimum velocity index — by measuring the non-dimensional maximum to minimum velocity ratio for the right and left common carotid arteries, and normalized each patient by dividing the larger by the smaller ratio to form a maximum/minimum index. This index for each patient was then compared to selective carotid arteriograms.

Methods

Common carotid artery Doppler wave-forms were recorded from a zero crossing directional Doppler (Parks Model 806-C). Only the forward flow component of the directional Doppler signal was used because jugular venous flow frequently distorts the differential signal. The differential Doppler signal was used to confirm the accuracy of the wave-form. Figure 1 illustrates the method of calculating the non-dimensional maximum to minimum ratio. All velocity wave-forms were recorded on a 2 channel strip chart recorder with the probe held in 2 or 3 different angles bilaterally. The mean value of 10 maximum and minimum signals was used for the final index value.

Over an 18 month period 136 consecutive patients had selective bilateral carotid arteriography and Doppler wave-form indices recorded. Of this group 57 patients had bilaterally normal or mildly stenosed carotid arteries, and 79 had 50% or greater stenosis of one or both common carotid arteries. Stenosis was measured by diameter at the narrowest dimension of the stenotic section divided by the distal normal internal carotid artery diameter. Patients were considered abnormal if the percent stenosis by diameter was greater than 50%. An additional 260 patients who did not have arteriography but were asymptomatic and had a normal multimethod non-invasive cerebral vascular screen (phonoangiography, pneumo-oculoplethysmography and periorbital Doppler exam) had common carotid Doppler velocity wave-forms measured.

Results

Beat to beat variability was present in individual velocity wave-forms in patients with arrhythmias and in some patients with a normal sinus rhythm. However, repeated measurement of the maximum to minimum ratio for a given carotid artery rarely varied by more than 20%. The inability of the non-dimensional (but not normalized) maximum to minimum ratio to separate normal from stenosed carotid arteries is illustrated in table 1.

Figure 2 is a histogram of the distribution of the non-dimensional and normalized maximum/minimum index in the 250 asymptomatic normal patients who did not have arteriography. Only 6% of these patients had an index greater than 1.25, and only 2.5% had an index greater than 1.30.

Figure 3 is a histogram of the distribution of the maximum to minimum index for 136 patients who had carotid arteriography. In 56 of the 60 abnormal patients who had an index greater than 1.30, the carotid artery with the most significant stenosis (right or left) had the larger maximum to minimum ratio. In the group of 14 patients with 50-75% stenosis 11...
TABLE 1. Non-dimensional but not Normalized Maximum to Minimum Common Carotid Doppler Velocity Ratios in 60 Carotid Arteries.

<table>
<thead>
<tr>
<th>% Stenosis</th>
<th>Maximum to Minimum Ratio mean ± 1 SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% (n = 20)</td>
<td>2.99 ± 1.123</td>
</tr>
<tr>
<td>85-99% (n = 20)</td>
<td>2.81 ± 1.031</td>
</tr>
<tr>
<td>100% (n = 20)</td>
<td>4.11 ± 2.312</td>
</tr>
</tbody>
</table>

Figure 1. Method of calculating the non-dimensional normalized Doppler velocity index from the recorded common carotid velocity wave-form. The non-dimensional components are maximum or peak velocity during systole (a) divided by minimum velocity during diastole (b). The normalization is produced by dividing the larger a/b by the smaller.

(78%) had an index greater than 1.25 and 9 (64%) had an index greater than 1.30. By contrast, of the 23 patients with one carotid artery completely occluded 22 (96%) had indices greater than 1.30. Table 2 gives the false positive, false negative, sensitivity, specificity, and accuracy data for the maximum/minimum index using 2 criteria of normal and abnormal. Figure 4 is the receiver operating characteristic (ROC) curve for the maximum/minimum index. The data points on the curve are for different index criteria for separating normal from abnormal patients.

Discussion

The use of Doppler velocity indices for detecting atherosclerosis is not new. Rutherford et al. used discriminant analysis to show that velocity wave-form analysis is useful in identification of normal and abnormal carotid arteries. Nicolaides et al. have shown in the common femoral artery that a non-dimensional velocity index, along with other wave-form parameters, is useful in predicting stenosis. The work reported here is new in that a single non-dimensional index, the maximum over minimum velocity, which is normalized to remove variability between individuals with similar carotid arterial systems, is used. Table 1 illustrates the wide variability of maximum to minimum ratios for carotid arteries with the same anatomy as well as the large overlap of ratios between normal, severely stenosed, and occluded arteries. Clearly the non-dimensional but not normalized maxi-

<table>
<thead>
<tr>
<th>Abnormal maximum/minimum index</th>
<th>Accuracy</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>False negative</th>
<th>False positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 1.25</td>
<td>86.8%</td>
<td>86.1%</td>
<td>76.0%</td>
<td>19/74</td>
<td>2/62</td>
</tr>
<tr>
<td>&gt; 1.30</td>
<td>96.5%</td>
<td>76.7%</td>
<td>96.5%</td>
<td>55/57</td>
<td>5/62</td>
</tr>
</tbody>
</table>

Figure 2. Histogram of the distribution of the non-dimensional normalized common carotid Doppler velocity index in 260 normal patients.
mum to minimum ratio is not useful in identification of abnormal carotid arteries. The maximum/minimum Doppler velocity ratio for the right or left carotid artery varies between normal patients by approximately 50% (table 1), but when the maximum to minimum velocity ratio is normalized the variability between normal patients is small as illustrated in figure 1. Accordingly, this test identifies patients with normal or abnormal arteries, not normal and abnormal arteries per se. However, we did find a high degree of consistency in predicting which side has the highest grade stenosis in patients with abnormal indices by examining the individual right and left carotid maximum to minimum ratio, the larger ratio being on the side with the highest stenosis.

The results of this study given in figures 3 and 4 and in table 2 indicate that the maximum/minimum index is very sensitive if an index of 1.30 or greater is used to identify abnormal patients. The choice of 1.30 gives a very low false positive rate and identifies approximately 75% of patients with carotid stenosis. Some specificity is lost by selecting a slightly lower abnormal index, such as 1.25, but this improves the sensitivity to 80–85%. The receiver operating characteristic (ROC) curve indicates that choosing the abnormal value to be lower than 1.25 gives an unacceptably high incidence of false positive results.

One could consider using other non-dimensional indices such as the mean over maximum velocity, or the mean over minimum velocity. However, the mean is a coupled variable. The maximum velocity and the minimum velocity are independent but the mean is an integral of the velocity curve with the maximum and minimum as end points and is therefore coupled to both. We have tried different indices and find that there is no advantage in using other velocity ratios. Further, the calculation of maximum over minimum is direct, easily done, and does not require integration. This index can be readily obtained with a directional Doppler and recorder with little experience or skill.

The physiologic reason for this index being abnormal in 75 to 80% of patients with carotid stenosis is not known. One possibility is that the atherosclerosis distorts the blood velocity wave-form in proportion to the degree of disease. If this hypothesis is correct then the maximum/minimum index is probably not necessarily specific for carotid stenosis located at the carotid bifurcation but may be abnormal with stenosis in other parts of the internal or common carotid system. We have found this to be true in several patients with intracranial disease as well as stenosis at the carotid bifurcation.

With the advent of better Doppler ultrasound instrumentation, in particular improvements in the zero velocity measurement which is critical in determining the maximum/minimum values, as well as the availability of frequency spectral analyzers, it may be expected that velocity indices will be more accurate, resulting in a more ideal receiver operating characteristic curve for this test.

References

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