Range-Gated Pulsed Doppler Power Frequency Spectrum Analysis for the Diagnosis of Carotid Arterial Occlusive Disease

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SUMMARY Carotid arterial disease was investigated with a Duplex Scanner using Power Frequency Spectrum Analysis. Sixty-one carotid systems were evaluated noninvasively and angiographically, while 20 controls were examined and assumed to be normal. Peak frequency and 50% frequency bandwidth, a quantitative index of spectral broadening, were correlated with the percentage of stenosis. Peak frequency predicted the presence or absence of hemodynamically significant stenoses (≥50% diameter reduction) with 90.8% accuracy, while 50% frequency bandwidth correctly identified similar lesions with 93.2% accuracy (p = NS). Also, with the latter results, carotid systems were grouped into <25%, 25% to 49%, and ≥50% stenosis categories with an 86.4% accuracy. Similar statistical evaluation was attempted for peak frequency results. It was not possible to separate hemodynamically insignificant lesions (<50% diameter reduction) into distinct groups because of the overlap of results among those arteries with <50% stenosis. Finally, all eight occluded internal carotid arteries were identified with combined Doppler/imaging analysis. However, with imaging alone, only 5 of 8 (63%) occluded arteries were correctly identified.

CAROTID ARTERIAL OCCLUSIVE DISEASE occurs most frequently in the carotid bifurcation, lending itself to easy detection by direct noninvasive ultrasonic techniques. Initially, bruit auscultation was the major physical finding that suggested carotid artery disease.1-3 Next, continuous-wave ultrasonic waveform analysis provided significantly more information.4-10 Finally, the duplex scanner, combining simultaneous real-time B-mode ultrasonic imaging with pulsed Doppler spectrum analysis represented a further advance.1-22

Blackshear and colleagues11 reported detection of 92% of all flow-limiting lesions (greater than 50%) in the internal carotid artery using the duplex scanner. Similar findings were reported by Fell and colleagues13 and Doorly and co-workers.23 However, these investigators, utilizing a subjective method of visually analyzing each Doppler velocity curve for spectral broadening, obtained less satisfactory results in detecting stenoses with less than 50% diameter reduction. In an effort to improve the detection of lesser degrees of disease, internal carotid artery to common carotid artery flow velocity (maximum and mean) ratios were examined.12, 18, 20 Use of these ratios improved the ability to detect hemodynamically insignificant lesions, but the data did not aid in quantitating the degree of stenosis.

Recently, Krause and colleagues24 applied power frequency spectrum analysis (PFSA) to carotid continuous-wave ultrasonic Doppler signals. The Doppler signals obtained during an 8-msec interval at peak systole were selected for further processing. Following frequency analysis, an amplitude versus frequency plot was obtained, and the bandwidth at 50% of peak amplitude (f_{50}) was determined. By examining the bandwidth at 50% of peak amplitude, Krause and co-workers were able to identify correctly all degrees of internal carotid artery stenosis with 91% accuracy. In this report, PFSA analysis of pulsed Doppler data from the carotid bifurcation was compared with angiographic findings.

Materials and Methods

Power frequency spectrum analysis was performed on the carotid arterial pulsed Doppler velocity signal from 115 patients and 10 healthy control subjects. Thirty-one patients (61 sites) subsequently underwent standard aortic arch and selective carotid arterial multiphase angiography. Each diseased arterial site was recorded and measured, and the percentage of diameter reduction determined. All 10 control subjects were less than 30 years of age and assumed to be free of carotid occlusive disease. The PFSA results from these 61 angiographically documented carotid arteries and 20 normal carotid arteries form the basis of this report.

In contrast to the usual method of spectrum analysis, in which Doppler velocity frequencies are analyzed as a function of time, in PFSA the power (or amplitude) of the recorded signal is plotted as a function of frequency. In this study, an image of the arterial system was obtained via a 7.5 mHz or 10.0 mHz B-mode ultrasonic probe,* depending on the depth of the vessel beneath the skin. After locating the vessel, a pulse repetition frequency was chosen to position a 3.0-mHz pulsed Doppler signal in the center of the vessel lumen. Several representative tracings from each arterial location were recorded and a 20-msec segment of the Doppler signal at peak systole was sampled. Peak systole was chosen because (1) it is the instant at which turbulence begins, and (2) it is a reliable landmark that can be identified easily and quickly. The information available in the peak systolic segment is the basis for

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power frequency spectrum analysis. Utilizing the output of a pre-programmed fast-Fourier transform, frequency is plotted on the X-axis, and the power (or amplitude) of the various frequencies is plotted on the Y-axis. In each sample, the frequency with the greatest amplitude receives a 100% power rating. Amplitudes of all other frequencies are then automatically calibrated in proportion. The equipment has software that computes the \( f_{\text{max}} \) bandwidth, \( f_{\text{max}} \), and \( f_{\text{mean}} \).

With the patient in the relaxed supine position, Doppler signals and power frequency spectra were obtained systematically from the common carotid artery starting approximately 1 cm above the clavicle and traveling cephalad to the carotid bifurcation. Next, the course of the internal (ICA) and external (ECA) carotid arteries were located, followed, and analyzed, initially at the bifurcation and then 1–2 cm distal to the bifurcation. Each vessel was identified both on the basis of its anatomic location and its specific audio signal. Additional signals were analyzed where any change in the audio signal or ultrasonic image suggested possible pathology.

Each power frequency spectrogram was analyzed for peak frequency (\( f_{\text{max}} \)) and frequency bandwidth at 50% of maximum power (\( f_{\text{max}} \)). A 50% frequency bandwidth was considered to represent a quantitative expression of spectral broadening. Both variables were compared with the corresponding angiographic findings.

Statistics

The unpaired t-test was used wherever applicable to determine statistical significance between two sets of measurements. Sensitivity was obtained by dividing true positive Doppler results by positive angiographic results. Similarly, specificity was calculated by dividing the true negative (normal) Doppler results by the negative (normal) angiographic results. Accuracy was determined by dividing the sum of true positive and negative Doppler results by the sum of positive and negative angiographic findings. The positive predictive value was obtained by dividing the true positive Doppler by the sum of true and false positive Doppler results. Negative predictive value was defined as true negative Doppler results divided by the sum of true negative and false negative results.

Results

A. Reproducibility

Ten carotid systems in control patients were re-studied by the same examiner approximately 30 minutes after the initial study was completed. A full examination was performed each time. Two measurements were taken from the internal carotid artery bilaterally in 5 control subjects. The initial examination yielded a mean of 210 ± 46 Hz (± standard deviation), while the mean of the second group of measurements was 200 ± 53 Hz (\( p = \text{NS, } t = 0.6127 \)). Three internal carotid arteries provided identical \( f_{\text{max}} \) measurements during the second measurement, while 6 studies were within 50 Hz of the original \( f_{\text{max}} \) measurement. Only one study had a difference of 100 Hz between the two examinations. Finally, the percentage of mean difference ± 1 S.D. between the respective measurements was 2.7 ± 25.8%. The resolution of spectrum analyzer read-out was 50 Hz.

B. Clinical Studies

Sixty-one carotid arterial systems from 31 patients underwent pulsed Doppler power frequency analysis (PFSA) and multiplanar carotid angiography. One patient underwent only a unilateral angiogram after experiencing an allergic reaction to the dye. Angiographically, the internal carotid artery exhibited minor wall irregularities or stenoses of less than 10% in 9 cases, while 13 vessels were 10–24% stenotic and 13 vessels exhibited 25–49% diameter reductions. In 26 vessels, hemodynamically significant stenoses were documented: 8 vessels were 50–74% stenotic, 10 vessels were 75–99% stenotic, and 8 vessels were occluded (table 1).

Frequency bandwidth at 50% peak power (\( f_{\text{max}} \)) and peak frequency (\( f_{\text{max}} \)) of each internal carotid artery velocity signal are compared with the angiographically determined percentages of diameter reduction in figures 1 and 2. A linear relationship was found for each analysis, with correlation coefficients of 0.920 and 0.889, respectively.

Receiver operator characteristic (ROC) curves were constructed to determine the optimal threshold \( f_{\text{max}} \) values to differentiate best between the presence or absence of disease a various levels of disease severity. Diameter reductions of 10%, 25%, and 50%, were chosen as the levels of angiographically determined disease to be used as the cutoff between the presence or absence of disease. As seen in figure 3, the optimal 50% frequency bandwidths to differentiate 10%, 25%, or 50% stenoses were 350 Hz, 1200 Hz, and 1750 Hz, respectively. Utilizing a \( f_{\text{max}} \) value greater than 350 Hz to predict greater than 10% stenosis, the test was 97.7% sensitive, 97.5% specific, and 97.6% accurate (table 2). An \( f_{\text{max}} \) value greater than 1200 Hz predicted a 25% diameter reduction with 80.7% sensitivity, and an \( f_{\text{max}} \) value of greater than 1750 Hz predicted a 50% diameter reduction with 94.4% sensitivity.

These criteria were re-grouped to evaluate further the ability of range-gated pulse Doppler PFSA to predict the degree of carotid arterial disease. In this analysis, frequency bandwidths (\( f_{\text{max}} \)) less than 1200 Hz were classified as less than 25% diameter reduction, \( f_{\text{max}} \) values of 1200–1750 Hz represented 25–49% stenosis, and values greater than 1750 Hz indicated great-

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**TABLE 1. Distribution of Internal Carotid Stenosis by Angiographic Measurements in 61 Vessels**

<table>
<thead>
<tr>
<th>Percentage of stenosis</th>
<th>10</th>
<th>10–24</th>
<th>25–49</th>
<th>50–74</th>
<th>75–99</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of vessels</td>
<td>9</td>
<td>13</td>
<td>13</td>
<td>8</td>
<td>10</td>
<td>8</td>
</tr>
</tbody>
</table>
er than 50% diameter reduction. The absence of an ICA signal was interpreted as a total occlusion. Using this scheme, there were 70 correct interpretations among the 81 vessels examined, for an accuracy of 86.4% (table 3). Six stenoses were overestimated (false-positive). In addition, one severe (95%) ICA stenosis was misinterpreted as an ICA occlusion.

Similar techniques were used to obtain the optimal peak frequency \( f_{\text{max}} \) to differentiate 10%, 25%, and 50%, stenosis. No acceptable value was found for 10% diameter reduction because there was significant overlap between the \( f_{\text{max}} \) values from vessels with less than 10% stenosis and those from vessels with 10–49% stenosis. Peak frequencies \( f_{\text{max}} \) of 2500 Hz and 3000 Hz were best found to classify vessels into the categories of greater than 25% and 50% stenosis, respectively.

To identify angiographic cases of 25% stenosis, the \( f_{\text{max}} \) criteria of 2500 Hz was 77.4% sensitive, 91.1% specific, and 85.5% accurate. Utilizing an \( f_{\text{max}} \) value of greater than 3000 Hz to predict 50% diameter reduc-

Discussion

Pulse Doppler frequency shift spectrum analysis was recently introduced as another noninvasive modality for the detection of carotid arterial occlusive disease. This method was described by Blackshear and colleagues, who accurately predicted the presence of 50% diameter reduction in the internal carotid artery with 92% sensitivity. However, the identification of lesser degrees of stenosis was not as accurate, a finding confirmed by Fell et al, Doorly et al, and Russell et al.

Several attempts to improve the accuracy of detecting carotid arterial stenoses of less than 50% have been reported. Measurements of peak frequency and of several ratios of internal to common carotid artery velocity have improved the accuracy of detecting hemodynamically significant le-
Frequency Spectrum Analysis data to quantitate spec-
noses (greater than 40%) with a specificity greater than 98%, 95% specific, and 95% accurate. For lesser degrees of stenosis, Rittgers et
al.10 calculated the systolic window of carotid artery
sions.12, 18, 20 For lesser degrees of stenosis, Rittgers et
al.10 calculated the systolic window of carotid artery
CW Doppler velocity tracings as a quantitative mea-
sure of spectral broadening. Among the parameters
examined, the distal ICA systolic window provided the
best sensitivity for detecting moderate to severe ste-
noes (greater than 40%) with a specificity greater than
85%.

Sheldon and coworkers22 utilized the ratio of max-
imum to mean frequency at peak systole from Power
Frequency Spectrum Analysis data to quantitate spec-
tral broadening. This investigators successfully de-
tected all stenoses greater than 40% and correctly iden-
tified all normal vessels (less than 20%). At the 25%
diameter reduction level, their data were 90% sensi-
tive, 98% specific, and 95% accurate.

Recently, Krause and colleagues24 reported their
preliminary experience with continuous-wave Doppler
PFSA to detect carotid arterial occlusive disease. Fre-
duency bandwidths at 50% peak power (f_{50%}) were
identified as an index of disease severity. For hemo-
dynamically significant lesions (greater than or equal
to 50% stenosis), the test was 100% sensitive, al-
though its specificity was only 45%. Utilizing greater
than 11% diameter reduction as the cutoff between the
presence or absence of internal carotid artery disease,
the sensitivity remained high (92%) and the specificity
increased to 83%. At this level, the peak frequency
(f_{m}) was 79% sensitive, but 100% specific.

The results of the present study support the PFSA
technique in the evaluation of pulsed Doppler frequen-
cy shifts in the carotid arterial system. The measure-
ment of peak frequency is sensitive to hemodynamical-
ly significant stenoses (greater than 50%), but its
sensitivity, specificity, and overall accuracy begin to
drop off in the detection of less severe disease. As seen
in figure 2, this decline in f_{m} accuracy is due to an
increased overlap between the values obtained from
the vessels with lesser stenoses and normals.

The frequency bandwidth at 50% of peak power
(f_{50%}) eliminates some of the limitations of peak fre-
cuency measurements. In the lesser disease catgories
(less than 50% stenotic), PFSA f_{50%} is most useful and
can be considered a quantitative index of spectral
broadening. The f_{50%} value at peak systole increased in
proportion to increasing vessel diameter reduction. As
seen in figure 1, there was little overlap between f_{50%}
values from various categories of disease severity, par-
ticularly with less than 50% stenosis. As diameter re-
duction approached 50%, the peak frequency of the
Doppler curve gradually increased in a linear fashion,
as noted in figure 2. However, the highest peak fre-
cuency recordable with the equipment used in this
study was 5000 Hz. Stenoses greater than 75% pro-
duce peak frequencies higher than 5000 Hz (fig. 2),
but f_{m} values greater than 5000 Hz could not be re-
corded. On the other hand, this drawback has been
remedied in the latest modification of the instrument.25

In addition to its capability to detect hemodynamical-
ly insignificant stenoses, f_{50%} determination can readi-
ly detect severe stenoses. As seen in Table 2, f_{50%}
identified stenoses greater than 50% with sensitivity of
94%, specificity of 93%, and accuracy of 93%. This
compares favorably with peak frequency measure-
ments. Using an f_{m} value of 3000 Hz to differentiate
50% diameter reduction, the f_{m} measurement was
89% sensitive, 91% specific, and 91% accurate.

One of the major advantages of the duplex scanner is
its ability simultaneously to image the vessel and visu-
alize the sampling site of the Doppler velocity sensor.
This technique aids substantially in the reliable detec-
tion of vessel occlusions. All 8 internal carotid artery
occlusions in this study were easily detected utilizing
both ultrasonic imaging and pulse Doppler PFSA.

### Table 2 Prediction of Internal Carotid Artery Stenosis by the Frequency Bandwidth at 50% of Peak Frequency (f_{50%}) Compared with Angiographic Measurements

<table>
<thead>
<tr>
<th>Angiographic percentage of stenosis</th>
<th>f_{50%} + Criterion</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>Accuracy (%)</th>
<th>Positive predictive value (%)</th>
<th>Negative predictive value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;10%</td>
<td>&gt;350 Hz</td>
<td>97.7</td>
<td>97.5</td>
<td>97.6</td>
<td>97.7</td>
<td>96.5</td>
</tr>
<tr>
<td>&gt;25%</td>
<td>&gt;1200 Hz</td>
<td>80.7</td>
<td>97.6</td>
<td>90.4</td>
<td>96.2</td>
<td>87.2</td>
</tr>
<tr>
<td>&gt;50%</td>
<td>&gt;1750 Hz</td>
<td>94.4</td>
<td>92.7</td>
<td>93.2</td>
<td>81.0</td>
<td>98.1</td>
</tr>
</tbody>
</table>

### Table 3 Correlation of Graded Degrees of Internal Carotid Artery Stenosis Predicted by the Frequency Bandwidth at 50% of Peak Frequency (f_{50%}) with Angiographic Measurements

<table>
<thead>
<tr>
<th>Angiographic stenosis (%)</th>
<th>1200 Hz</th>
<th>1200-1740 Hz</th>
<th>1750 Hz</th>
<th>No audible Doppler signal</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-24</td>
<td>41</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>42</td>
</tr>
<tr>
<td>25-49</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>50-99</td>
<td>0</td>
<td>0</td>
<td>17</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Totals</td>
<td>46</td>
<td>5</td>
<td>21</td>
<td>9</td>
<td>81</td>
</tr>
</tbody>
</table>

Accuracy = 70/81 = 86.4%.
However, three of these vessels would not have been definitively diagnosed as occluded had the ultrasonic imager been used alone; consequently, both imaging and frequency analysis are necessary to predict accurately the total vessel occlusion. However, a very tight stenosis was misdiagnosed as occluded in the present study. The patient had a 95% internal carotid artery stenosis, but the lumen could not be visualized nor was flow detected with the pulsed Doppler system. Two explanations for this error are possible: (1) the very tight stenosis became occluded soon after angiography prior to the noninvasive evaluation; or (2) the Doppler sample volume missed the narrow jet of blood squirting through an extremely tight stenosis. The recent introduction of a variable sample volume pulsed Doppler should remedy this deficiency.

Our data support the quantitative index of the $f_{50\%}$ analysis from a range-gated pulsed Doppler. It not only detected hemodynamically significant stenoses but also correlated linearly with the degree of hemodynamically insignificant stenoses. On the other hand, peak frequency ($f_{50\%}$) values greater than 3.0 kHz were useful to confirm $f_{50\%}$ indices of hemodynamically significant stenoses.

### Table 4: Prediction of Internal Carotid Artery Stenosis by the Peak Frequency ($f_{50\%}$) Compared with Angiographic Measurements

<table>
<thead>
<tr>
<th>Angiographic percentage of stenosis</th>
<th>Peak frequency criterion (Hz)</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>Accuracy (%)</th>
<th>Positive predictive value (%)</th>
<th>Negative predictive value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;25%</td>
<td>&gt;2500 Hz</td>
<td>77.4</td>
<td>91.1</td>
<td>85.5</td>
<td>80.7</td>
<td>83.7</td>
</tr>
<tr>
<td>&gt;50%</td>
<td>&gt;3000 Hz</td>
<td>88.9</td>
<td>90.8</td>
<td>91.6</td>
<td>80.0</td>
<td>96.1</td>
</tr>
</tbody>
</table>

References

25. DRF-400 Operator Guide, Diasonics Corporation, Milpitas, CA September, 1983
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