Doppler Power Frequency Spectrum Analysis in the Diagnosis of Carotid Artery Disease

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SUMMARY Power Frequency Spectral Analysis (PFSA) which evaluates the power of the frequency components at a selected interval, was applied in this preliminary study using a 5MHz Doppler continuous wave flow velocity meter and a modified Edwards Spectraview 500 analyzer.

PFSA was used to study the common, internal and external carotid arteries of ten young adult control subjects and 31 patients with angiographically documented carotid bifurcation lesions. Two useful indices are described: (1) the frequency band width at 50% of maximum power (f Mü) and (2) the highest frequency recorded (f max). An f Mü wider than 1900 Hz (corresponding to spectrum broadening) identified stenoses as low as a 15% diameter reduction. An f max higher than 6500 Hz practically always indicated a 50% or greater diameter reduction.

Eighty two percent of stenoses with 11–25% diameter reduction were detected, as were 95% of stenoses from 36–50%. All stenoses from 51–99% were identified.

CURRENTLY USED METHODS for non-invasive diagnosis of extracranial carotid artery disease are based primarily on the indirect and direct assessment of the local hemodynamic disturbances. The indirect methods are based on changes in the flow velocity pattern of the supraorbital or frontal artery5-7 or on phase related eye volume changes8 or on indirect intraocular pressure measurements.9 The direct methods include Doppler direct flow velocity evaluation of the carotid bifurcation,10-11 or more complex imaging techniques using either the Doppler velocity signal to delineate the examined vessel12-15 or various modifications of the real time B-mode scanner16 which provide pathoanatomic information. An additional degree of sensitivity was added by the introduction of carotid artery velocity spectrum analysis.17-21 The simultaneous combination of a real time B-mode scanner with spectrum analysis (the "Duplex scanner") has yielded very encouraging results.16 Blackshear and co-workers22 also reported using such a B-mode scanning system in combination with a real time frequency spectrum analysis of the whole velocity cycle.

Since the onset of turbulence occurs at the peak velocity or very shortly after23-26 and because this is also a well defined landmark, we selected for our analysis a short but critical period of Doppler shift frequency at peak systole. This permits Power Frequency Spectrum Analysis (PFSA) in which the power of the Doppler shifted signal is presented as a function of the frequencies involved. In this preliminary report, non-invasive PFSA results obtained with a C-W Doppler are compared with carotid artery angiography.

Method
To perform power frequency analysis, a commercially available power frequency analyzer utilizing a preprogrammed Fast Fourier Frequency Transform system (Spectraview 500, American Edwards Labs, Santa Ana, CA) was modified to our specifications, based on preliminary results obtained with a laboratory power spectrum analyzer. The modifications included an expanded frequency range (up to 20 kHz) with a frequency resolution of 128 Hz and time resolution of 6 msec and proper impedance matching to accept the audio output from commercially available Doppler Velocity Meters. In these studies, the 5 MHz channel of a 906 Parks Electronics C-W Doppler Velocity Meter was used.

The studies were performed on subjects in a supine position systematically monitoring the signals from the proximal common carotid artery (CCA), about 1 cm above the clavicle, up to the bifurcation. At that point, the course of the internal (ICA) and external carotid artery (ECA) respectively was followed to the angle of the mandible on the basis of their different audio signals.7-10,24 Power frequency spectrum analysis (PFSA) was performed routinely at the following sites: 1) CCA, 1 cm above the clavicle; 2) CCA, just below bifurcation; 3) ICA, and 4) ECA, just above the carotid bifurcation; 5) ICA and 6) ECA, at the level of the mandibular angle. In addition, an analysis was performed at every site in which a change of audio signal was observed.11,25 In this study only the forward audio signals were analyzed.

The results reported here are based on studies performed on ten young healthy control subjects (age 19–32 years) and on 31 patients (age 49–77 years) in whom carotid angiography had been undertaken for a variety of indications. The evaluation was double blind, with an experienced neurovascular radiologist...
evaluating the angiograms independently of the PFSA.

The arteriograms used in this study were obtained by selective common carotid artery injections and both oblique and lateral views of the carotid bifurcation were used. A magnification correction factor of 25% was experimentally established. The percentage diameter reduction was obtained by dividing the narrowest diameter by the next distal intact segment diameter, multiplied by 100. The angiographic classification was as follows:

A Smooth vessel wall without any signs of disease
B1 Irregular vessel wall, or circumscript encroachment
   \( \leq 10\% \) diameter reduction
B2 Encroachment with 11–25\% diameter reduction
B3 26–50\% diameter reduction
C 51–75\% diameter reduction
D 76–99\% diameter reduction
E Complete occlusion

The examination was performed as follows: the proper probe position to obtain the maximum Doppler velocity signal was first identified by scanning the site of measurement and then changing the angle of the probe to obtain the maximum velocity amplitude from the Doppler velocity meter, monitored either on an oscilloscope or on a recorder (the method has been described previously in a report on lower extremity arterial Doppler velocity evaluation.26) This signal was then stored in the Spectraview 500 and an electronic cursor on the screen was positioned at peak systole. Six cardiac cycles were usually analyzed and averaged and the power frequency spectrogram was displayed and recorded. In cases of arrhythmias the number of analyzed cycles was reduced to two. A preprogrammed microprocessor normalized the maximum power as 100\% and determined the threshold noise level as well (at 40dB). A simultaneously recorded ECG was used as a continuous reference signal. The spectrogram was evaluated as follows:

a) the highest frequency component \( f_{\text{max}} \) (fig. 1)

b) the difference between the highest and lowest frequency at the 50\% (or \(-3\) dB) power level \( f_{50\%} \). This can also be defined as the frequency band width at 50\% peak power.

**Reproducibility**

Repeat studies were performed on five control subjects three times in 15 minute intervals. On both sides of the neck the following sites were measured: common carotid artery — 1 cm above the clavicle and just below the bifurcation and internal carotid artery — just above the bifurcation and at the most distal site (usually at the level of the jaw). The \( f_{50\%} \) and \( f_{\text{max}} \) values were evaluated and the percentage difference from the mean value was calculated as follows:

\[
\frac{\Delta M}{M} \times 100
\]

**Results**

Twenty-four measurements were taken in each of the 5 control subjects in whom the reproducibility was studied (4 measurements on each side of the neck = 8 measurements and repeated 3x = 24 measurements performed on each of the 5 control subjects). The results are summarized in table 1 indicating the reproducibility of the \( f_{50\%} \) determinations in all four measurement sites, with a mean difference between subsequent measurements ranging from 29.4\% to 35.4\% (st. dev. \pm 14.2 and 15.8 respectively). The reproducibility for \( f_{\text{max}} \) is better, with a mean percentage difference ranging from 6.8\% to 13.0\% (st. dev. \pm 6.07 and 12.56 respectively). The probable reason for this difference is discussed later.

![Figure 1. Power Frequency Spectrum tracings of: a) normal common carotid artery \( f_{50\%} 1050 \text{ Hz}, f_{\text{max}} 3398 \text{ Hz} \) and, b) internal carotid artery \( f_{50\%} 777 \text{ Hz}, f_{\text{max}} 2490 \text{ Hz} \). Horizontal axis: frequency and vertical axis: power of the respective frequency components. Peak representing 100\% Cursor indicates maximum frequency \( f_{\text{max}} \).](http://stroke.ahajournals.org/)
TABLE 1 Reproducibility Study

<table>
<thead>
<tr>
<th>Internal carotid artery</th>
<th>Common carotid artery</th>
</tr>
</thead>
<tbody>
<tr>
<td>bifurcation jaw</td>
<td>clavicle bifurcation</td>
</tr>
<tr>
<td>$f_{50}$</td>
<td>$f_{50}$</td>
</tr>
<tr>
<td>29.4%</td>
<td>33.4%</td>
</tr>
<tr>
<td>± 14.2</td>
<td>± 15.8</td>
</tr>
<tr>
<td>S.D. ± 14.2</td>
<td>± 15.8</td>
</tr>
<tr>
<td>$f_{\text{max}}$</td>
<td>$f_{\text{max}}$</td>
</tr>
<tr>
<td>6.8%</td>
<td>7.7%</td>
</tr>
<tr>
<td>± 6.1</td>
<td>± 4.8</td>
</tr>
<tr>
<td>S.D. ± 6.1</td>
<td>± 12.5</td>
</tr>
</tbody>
</table>

$\Delta M / M \times 100$ where $\Delta M =$ difference between consecutive measurements, and $M =$ mean of the consecutive measurements.

I. Normal Control Subjects

The results obtained from bilateral examinations of ten young healthy subjects are detailed in table 2. Figure 1 displays the power frequency spectra of a normal CCA and a normal ICA. Spectra like these, with a narrow $f_{\text{max}}$ band width, a low $f_{\text{max}}$ and well defined peak (without perturbation), could be recorded in all normal carotid arteries.

The $f_{\text{max}}$ values obtained from the CCA varied from 2400 to 5500 Hz while those obtained from the ICA ranged from 2400 to 4500 Hz.

The frequency band-width at 50% power ($f_{\text{max}}$) varied from 630-1300 Hz and 580-1300 Hz for the CCA and ICA respectively (table 2). In normals the $f_{\text{max}}$ band width was remarkably narrow and uniform (e.g. low standard deviation) and none of the $f_{\text{max}}$ values exceeded 1300 Hz. Similar uniformity was not observed in the ECA, where the $f_{\text{max}}$ ranged from 200-5600 Hz and the $f_{\text{max}}$ from 830-2970 c/s. In the external carotid artery, deviations were also higher.

II. Clinical Studies

A) Angiographic Findings

Of 31 patients who underwent carotid artery angiography, 28 were studied bilaterally and three on one side only. Two additional ICA sites due to independent stenoses were evaluated separately. Data from four external carotid arteries were excluded because of the angiographer's equivocation regarding the precise origin of the vessel. In 6 cases, the ICA was occluded and therefore, no signal was obtained; these cases were not included in the frequency analysis.

B) Power Frequency Spectrum Analysis

Internal Carotid Artery

The $f_{\text{max}}$ values obtained from 55 internal carotid arteries (ICA) are plotted (fig. 2) against the angiographically measured arterial diameter at the site of the stenosis (the six completely occluded ICAs are not included in fig. 2). The essentially flat part of the graph from 7 to 11 mm is mainly due to cases in which the carotid sinus bulb was larger than the distal segment of the artery and was listed as zero reduction in diameter even in the presence of some uneven radio-opacity. In figure 3, the relationship between $f_{\text{max}}$ and the percentage reduction of diameter is displayed. Similarly, Figure 4 depicts the relationship between the band width at 50% power level ($f_{\text{max}}$) and percentage reduction of diameter is displayed. A line has been drawn at an $f_{\text{max}}$ above 1900 Hz and $f_{\text{max}}$ above 4500 Hz respectively, which separates both the normal from clearly pathologic data.

It can be seen (fig. 4) that an $f_{\text{max}}$ of 1900 Hz represents a fairly good separation line between completely normal or only irregular vessels (group A and B) while percentages of diameter reduction larger than 11% were associated with an $f_{\text{max}}$ higher than 2000 Hz. The sensitivity of the test increased with increasing percentage reduction of diameter as illustrated in tables 3.
and 4. If groups B3-D (> 11% diameter reduction) are considered positive (table 4), specificity for \( f_{\text{max}} \) and \( f_{\text{mix}} \) is 88% and 100% respectively, while sensitivity for \( f_{\text{mix}} \) and \( f_{\text{max}} \) is 92% and 79% respectively. If groups B3-D (>26% diameter reduction) are considered positive, specificity decreases to 65% and 85% respectively, while the sensitivity increased to 97% and 90% respectively. All of the vessels in groups C and D (51–99% diameter reduction) could be identified on the basis of a \( f_{\text{mix}} \) higher than 1900 Hz (table 3).

The \( f_{\text{max}} \) value seems to be a very useful index in the assessment of the degree of severity of obstruction. Out of 15 stenoses classified angiographically in groups C and D, all 15 exhibited a \( f_{\text{max}} \) higher than 6500 Hz (see table 3 and fig. 3).

Figure 5 illustrates the data in a case of mild stenosis (35% diameter reduction) and the corresponding PFSA values. It can be seen that the \( f_{\text{mix}} \) is 3014 Hz while \( f_{\text{max}} \) is 4511 Hz confirming the presence of a flow disturbance despite its mild degree.

On the other hand, figure 6 depicts a typical example of high grade stenosis (69% diameter reduction) which is identified by the combination of a widened \( f_{\text{mix}} \) value (5541 Hz) and a high \( f_{\text{max}} \) (8261 Hz).

### Common Carotid Artery

CCA

The PFSA results of the CCA were similar to those described above for the ICAs. In forty-six angiographically normal CCAs (Group A), the \( f_{\text{mix}} \) was <1600 Hz in all, and exceeded 1406 Hz in only two cases (1582 and 1755 Hz). Similarly, \( f_{\text{max}} \) ranged from 1523 to 4450 Hz. The highest \( f_{\text{mix}} \) values were approximately 1000 Hz lower than the highest \( f_{\text{mix}} \) obtained in the CCA of the young control group (see table 2).

In table 5 the results of angiographic evaluation are compared with the \( f_{\text{mix}} \) and \( f_{\text{max}} \) data obtained in the CCA. For the common carotid artery, a \( f_{\text{mix}} \) above 1900 Hz and \( f_{\text{max}} \) higher than 5500 Hz were considered pathologic. All lesions above 11% diameter reduction were identified by the \( f_{\text{mix}} \) (10 instances). Combined results of the ICA and CCA are given in table 6.
severity of the disease with the PFSA values. In addition, less time and effort was spent in attempting to detect disease in the ECA (when compared to the ICA and CCA) because of its lesser clinical relevance, especially in the presence of disease in the ICA or CCA.

Discussion

It was established that broadening of the frequency spectrum obtained from the Doppler audio signal reflects to some extent, the degree of turbulence induced by arterial stenosis. In all these studies, the frequency components were continuously analyzed throughout the cardiac cycle. The broadening of the frequency spectrum is usually classified in different categories either on the basis of the presence or absence of a signal-free "window" during peak systole, or on the basis of an increase in systolic peak frequency. A more quantitative approach to express spectrum broadening was described by Bodily and co-workers who used the ratio of the difference and sum of the maximum and minimum frequency at peak systole in addition to the mean frequency, again at peak systole.

Power Frequency Spectrum Analysis (PFSA) permits analysis of spectral broadening more exactly by electronically selecting a certain time interval in which all frequency components are analyzed and displayed as a function of their relative power. In this study it could be shown that the band width widening at 50% of peak power, is a well definable reference point. The time interval to be analyzed can be selected by positioning the electronic cursor. We selected to analyze the interval at peak systole because it is a well defined landmark and it also coincides with the earliest onset of flow disturbances, although the intensity of flow disturbance may increase during the phase of deceleration.

The results presented in this report establish the diagnostic usefulness of the power frequency spectrum analysis (PFSA) approach, which provides two well-defined and practical indices: the maximum frequency contained in the sample signal ($f_{\text{max}}$) and the frequency band width at 50% power level ($f_{50\%}$).

The reproducibility of $f_{\text{max}}$ is better than that of $f_{50\%}$ (table 1). The cause of this difference is probably related to the fact that $f_{\text{max}}$ is essentially the difference between two frequencies — the frequency on the descending minus the frequency on the ascending limb of the power vs. frequency curve — see e.g. figure 1. While the determination of $f_{\text{max}}$ requires only one value, $f_{50\%}$ requires two values and this may increase the error of measurement and thus decrease the reproducibility.

The reported results demonstrate that an increased $f_{50\%}$ value (i.e., a widened frequency band at 50% power level) reflects the presence of a flow disturbance induced by a 15% or greater than 15% diameter reduction. For instance, a $f_{50\%}$ of 3000 Hz or more, indicates the presence of a stenosis of at least 25% reduction of diameter (Group B3, fig. 4). In turn, the $f_{\text{max}}$ index is slightly less sensitive, but when combined with the $f_{50\%}$ confirms the diagnosis. In addition, it is very helpful in gauging the severity of the constriction. A $f_{\text{max}}$ value of 6500 Hz or more is highly indicative of a 50% diameter reduction or more (fig. 3). These results are basically in line with previous reports according to which a...
Table 5  Correlation of Power Frequency Spectrum Analysis and Angiographic Data for the Common Carotid Artery*

<table>
<thead>
<tr>
<th>Angiographic classification</th>
<th>Diameter reduction (%)</th>
<th>f_{500} (Normal)</th>
<th>f_{500} (Pathologic) (&gt;1900 Hz)</th>
<th>f_{max} (Normal)</th>
<th>f_{max} (Pathologic) (&gt;5000 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>46</td>
<td>0</td>
<td>46</td>
<td>0</td>
</tr>
<tr>
<td>B1</td>
<td>&lt;10</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>B2</td>
<td>11−25</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>B3</td>
<td>26−50</td>
<td>0</td>
<td>6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>51−75</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>76−99</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

*28 CCAs were studied bilaterally and 3 unilaterally (2 x 28 + 3) = 59.

"Spectral broadening", corresponding to an increase in f_{500} could be detected in low grade stenoses without a significant increase in peak frequency, while high grade stenoses were always accompanied with a significant increase in peak frequency (corresponding to f_{max}).

The PFSA results from the ECA are less precise and the explanation for this is not clear at the present time. Most probably the highly variable topography, winding course and overlying branches may be important factors. Fortunately, the clinical significance of obstructions in the ECA are less frequently compelling when compared with the ICA or CCA.

The five data points in Group B1, with an f_{500} below 1900 Hz (fig. 4) indicate that the flow disturbance produced by diameter encroachments of 10% or less, were below the threshold of detection of this system. At the other extreme, although the overall results (false positive and false negative) in Groups B2, B3, C and D correlate well with the angiographic findings, including a very low 3.5% false positive rate for the normal vessels, the two missed ICA occlusions out of six represent a problem to be discussed.

Table 6  Correlation of Power Frequency Spectrum Analysis and Angiographic Data for Both Common and Internal Carotid Arteries

<table>
<thead>
<tr>
<th>Angiographic classification</th>
<th>Number of arteries</th>
<th>Combined</th>
<th>False +</th>
<th>False −</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>% diam. reduct.</td>
<td>normal</td>
<td>pathologic</td>
<td>False + (3.5%) = 2/58</td>
</tr>
<tr>
<td>A</td>
<td>0</td>
<td>58</td>
<td>56</td>
<td>2</td>
</tr>
<tr>
<td>B1</td>
<td>10</td>
<td>8</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>B2</td>
<td>11−25</td>
<td>11</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>B3</td>
<td>26−50</td>
<td>20</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>C</td>
<td>51−75</td>
<td>14</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>D</td>
<td>76−99</td>
<td>3</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>E</td>
<td>100</td>
<td>6</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

False + = \frac{PFSA +}{Angiography −}  False − = \frac{PFSA −}{Angiography +}

The technique itself requires a meticulous and systematic approach and a sound knowledge of the vascular topography of this region. To improve the reliability of the diagnosis, it was worthwhile repeating every measurement which yielded a pathologic result at least once. Interference with venous velocity signals must be avoided completely. With increasing experience the number of incorrect diagnostic conclusions should decline. However, the special hemodynamics of the IC and EC vascular beds contribute to these difficulties to some extent. In both described false negative cases of internal carotid artery occlusion, in spite of careful scanning around the bifurcation, the external carotid artery with its atypical diastolic flow component, acquired in the presence of an occluded ICA, successfully simulated a patent ICA, while another branch of the ECA masquerading as the ECA. It is conceivable that the likelihood of such an error may be substantially reduced if PFSA analysis were used in conjunction with a real time B-mode imaging system.

We think that the availability of a velocity based imaging system, although otherwise very useful, would not have prevented this error.
From a practical point of view, however, this inadequacy of the technique may be compensated for by complementing the direct PFSA carotid artery examination with one of the indirect plethysmographic techniques, such as oculoplethysmography as described by Kartchner-McRae or Gee-pneumocapuloplethysmography. Both techniques, though not very sensitive below about 60% diameter reduction, are very reliable with extreme stenoses or occlusions. When compared with direct non-invasive diagnostic techniques, such as real time B-mode imaging or various types of velocity based imaging systems, it should be emphasized that the additional frequency analysis of the Doppler velocity signal still may add a further level of sophistication to the study. Whether human ear frequency discrimination capability is utilized or some type of electronic frequency analysis is employed for this purpose, is a matter of personal experience and availability of a suitable device. However, electronic processing has the advantages of providing quantitative data which may be recorded, preserved and objectively evaluated.

The data presented suggest that power frequency spectrum analysis will improve the early diagnosis of extracranial carotid artery occlusive disease and will also be useful in the follow-up of patients post carotid endarterectomy where the detection of early small flow disturbances may be important in clinical decision making.

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