Continuous-Wave *Versus* Range-Gated Pulsed Doppler Power Frequency Spectrum Analysis in the Detection of Carotid Arterial Occlusive Disease

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Two types of ultrasonic Doppler velocity metering devices currently used in the detection of extracranial carotid artery disease, the continuous-wave (CW) and the range-gated pulsed (RP) Doppler systems, were compared in the present study. Power frequency spectrum analysis (PFSA) was performed on 130 carotid arterial bifurcations with a CW Doppler and 81 carotid arteries with an RP Doppler system. All results were compared with angiographic findings. The frequency bandwidth at 50% peak power ($f_{50\%}$), a quantitative index for defining spectral broadening, detected stenoses equal to or greater than 50% diameter reduction with 93% sensitivity, 92% specificity, and 92% accuracy with the CW system. With the RP Doppler, the same degree of stenosis was identified with 94% sensitivity, 93% specificity, and 93% accuracy. Compared with angiographic classification into 0–24%, 25–49%, and 50–99% diameter reduction categories, CW Doppler PFSA and an 85% overall accuracy, and the RP Doppler overall accuracy was 86%. CW Doppler also correctly identified 15 of 16 internal carotid artery (ICA) occlusions; 8 of 8 ICA occlusions were correctly identified with the RP Doppler. Thus, both techniques detected carotid artery disease with comparable results. For research and ease of operation, an RP Doppler system with a variable sampling volume appears to be most desirable. However, a standard CW system is superior if utility and cost-effectiveness are of prime importance.

CURRENTLY, TWO DIFFERENT ultrasonic Doppler velocity metering systems are used in the detection of extracranial carotid artery disease: the continuous-wave (CW) and the range-gated pulsed (RP) Doppler system. Utilizing CW Doppler spectral analysis, Barnes et al.[1] demonstrated a 98% sensitivity for detecting hemodynamically significant lesions (greater than 50% stenosis). Similar results have been reported by Brown et al.[2] and Krause et al.[3] With the combined technique of ultrasonic imaging and RP Doppler spectrum analysis (duplex scanning), Blackshear et al.[4] demonstrated 92% accuracy for detecting internal carotid artery lesions greater than 50% diameter reduction. This finding was subsequently confirmed by Fell et al.,[5] Doorly et al.,[6] and Matsumoto et al.[7]

In this report, two separate patient populations were examined utilizing power frequency spectrum analysis (PFSA) of Doppler shifted signals obtained from either a CW or RP Doppler system. Each individual patient study was compared with angiographic information, and a comparison was made between the findings with the two Doppler systems.

Methods and Materials

Two separate patient populations underwent direct noninvasive carotid arterial testing utilizing PFSA.[3] The first population (Group A) was investigated with a bidirectional CW Doppler velocity meter (Parks 906, Parks Electronics, Beaverton, OR), whose output was fed into a modified Spectraview 500 Analyzer (American Edwards Laboratories, Santa Ana, CA). The second population (Group B) underwent RP Doppler examination with an associated B-mode ultrasonic imager (Diasonics, Milpitas, CA). Both groups were examined by the same investigator. Each patient subsequently underwent standard aortic arch and selective carotid angiography. All disease sites were recorded and a per cent internal carotid artery diameter reduction calculated.

The PFSA technique has been reported in detail[3] and will be described here briefly. The power (or amplitude) of the recorded signal was plotted as a function of frequency. This is in contrast to the usual time domain spectrum analysis in which frequencies are recorded as a func-

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tion of time. In the CW Doppler system, the carotid arterial flow velocity signal was obtained using a 5.2 mHz probe. The audio output was fed into a modified spectrum analyzer (Spectraview 500). A 10 msec segment of the Doppler signal at peak systole was sampled. Peak systole was chosen for two reasons: (1) it is the moment at which turbulence develops at the earliest stage of stenosis, and (2) it is a reliable landmark that can be easily and quickly identified. Three to nine consecutive cardiac cycles were sampled.

The information available in the 10 msec segment served as the basis for PFSA utilizing a preprogrammed Fast Fourier transform. The power (or amplitude) of the Doppler signal was plotted against the corresponding frequencies. The frequency with the highest amplitude received a 100% rating and subsequently each frequency composing the Doppler signal was given a percentage rating according to its amplitude or power. This set of frequencies was displayed and printed as a power frequency spectrogram.

With the patient in a relaxed, supine position, CW Doppler PFSA was performed, beginning 1 cm above the clavicle and progressing cephalad to the carotid bifurcation. The courses of the internal carotid (ICA) and external carotid (ECA) arteries were identified by their differing audio signals and subsequently followed cephalad to the angle of the mandible. At various positions along each artery, a power frequency spectrogram was produced.

With the duplex system, an image of the carotid bifurcation was obtained using a 7.5 mHz or 10.0 mHz B-mode ultrasonic probe, the choice of probe depending on the depth of the vessel under 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, with a monitored beam angle of approximately 45–60°, to obtain an appropriate arterial flow velocity signal. Several representative tracings from an individual arterial location were recorded, and PFSA was performed on a 20 msec section of peak systolic Doppler signals, as just described. Power frequency spectrograms were obtained systematically from the common carotid artery approximately 1 cm above the clavicle cephalad to just proximal to the bifurcation. Again, each branch vessel was identified on the basis of both its anatomic location and its different audio signal.[1] Additional signals were analyzed at the location of any change in the audio signal or ultrasonic image implying a possible site of disease.

Power frequency spectrograms from both techniques were analyzed for peak frequency (f_{max}) and frequency bandwidth at 50% of peak power ($f_{50\%}$), variables that are considered to represent a quantitative expression of spectral broadening.[3] Both variables were compared with corresponding angiographic findings to determine their effectiveness in identifying carotid pathology.

TABLE 1. *Angiographic Classification of Carotid Stenosis in Patients Undergoing Noninvasive Testing with CW or Pulsed Doppler Instruments*

	Degree of Stenosis (% Diameter)					
Doppler Type	0–10	10–24	25–49	50–74	75–99	100
Group A						
Continuous wave	33	6	34	23	19	16
Group B						
Range-gated pulsed	29	13	13	8	10	8

From January 1983 to September 1983, 130 carotid arterial systems from 66 patients underwent CW Doppler PFSA and multiplanar carotid angiography (Group A). From October 1983 to March 1984, 81 carotid arterial systems from 41 patients underwent RP Doppler PFSA and multiplanar carotid angiography (Group B).

Results

Angiographically, the internal carotid arteries from Group A CW Doppler exhibited minor wall irregularities or stenoses of less than 10% in 33 vessels, six arteries were 10–24% stenotic, 34 arteries were 25–49% stenotic, and 42 vessels exhibited hemodynamically significant stenoses: 23 arteries were 50–74% and 19 arteries 75–99% stenotic. In addition, 16 internal carotid arteries were totally occluded (Table 1). In Group B, (RP Doppler), 29 arteries exhibited minor wall irregularities or stenoses less than 10%, 13 were 10–24% stenotic, and 13 arteries exhibited 25–49% diameter reduction. Twenty-six vessels contained flow-reducing stenoses (8 arteries were 50–74% and 10 arteries were 75–99% stenotic), while eight internal carotid arteries were occluded.

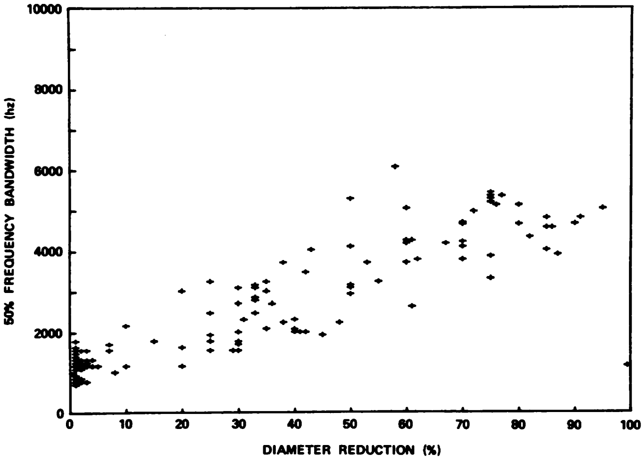

FIG. 1. Frequency bandwidth at 50% peak power calculated from continuous-wave Doppler power frequency spectrum analysis compared with angiographically determined per cent diameter reduction (r = 0.723).

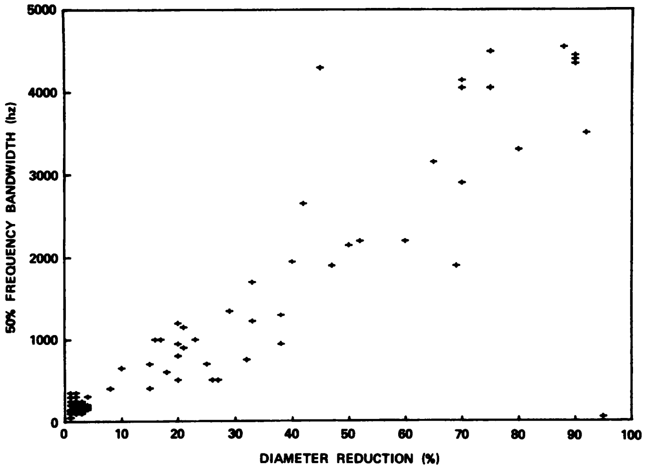

FIG. 2. Frequency bandwidth at 50% peak power calculated from range-gated pulsed Doppler power frequency spectrum analysis compared with angiographically determined per cent diameter reduction (r = 0.942).

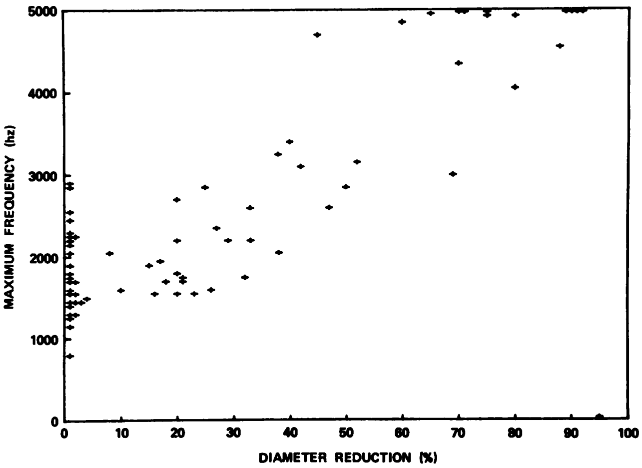

FIG. 4. Range-gated pulse Doppler peak frequency compared with angiographically determined per cent diameter reduction (r = 0.889).

The $f_{50\%}$ of each internal carotid artery signal was compared with the angiographically determined per cent diameter reduction for each technique, as seen in Figures 1 and 2. Each correlation exhibited a linear relationship. Using the CW Doppler, the correlation coefficient was 0.723, while with an RP Doppler the correlation coefficient was 0.942.

A similar comparison was made between angiographic results and the f_{max} of each ICA velocity signal generated by the two respective techniques (Figs. 3 and 4). Again, linear relationships were found to exist. With the CW Doppler, the correlation coefficient was 0.854, and with the RP Doppler it was 0.889.

Optimal threshold $f_{50\%}$ values to best differentiate the presence or absence of disease at various levels of disease severity were determined by preparing receiver operator characteristic curves for each Doppler technique.[9,10] Diameter reductions of 10, 25, and 50% were chosen as the level of angiographically determined disease to be used as cutoffs for the presence of significant disease. With the CW Doppler, the optimal threshold $f_{50\%}$ values to differentiate lesions at 10, 25, or 50% stenosis were 1600, 1800, and 3200 Hz, respectively. Using an $f_{50\%}$ value of 1600 Hz or more to predict 10% stenosis, the test was 94% sensitive, 91% specific, and 93% accurate. Table 2 documents the precision of the method at other degrees of stenosis. With an RP Doppler, an $f_{50\%}$ value of more than 350 Hz predicted 10% stenosis with 98% sensitivity, 98% specificity, and 98% accuracy. Similar results were obtained at other levels of stenosis (Table 3).

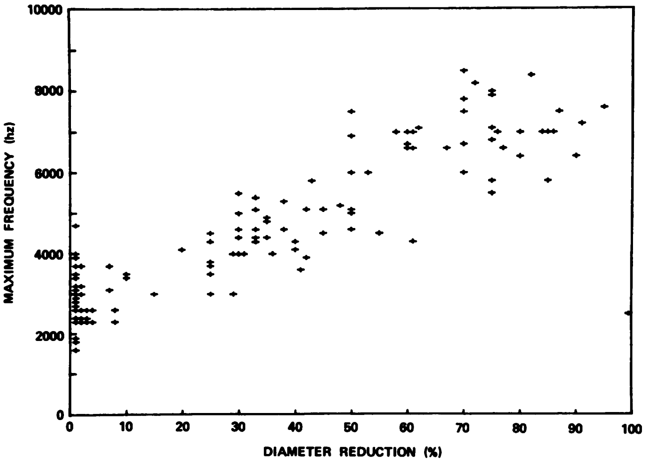

FIG. 3. Continuous-wave Doppler peak frequency compared with angiographically determined per cent diameter reduction (r = 0.854).

These criteria for each technique were grouped to evaluate further their ability to predict carotid arterial disease. With the CW Doppler, $f_{50\%}$ bandwidths less than 1800 Hz were used to predict less than 25% diameter reduction, while 1800 to 3200 Hz were considered to represent 25–49% stenosis, and greater than 3200 Hz was classified as at least a 50% diameter reduction. The absence of an ICA signal was considered to represent a total occlusion (Table 4). In all, among the possible 130 vessels examined, there were 111 correct classifications for an 85.4% accuracy. There were 10 underestimated stenoses (relative false-negatives), and 9 stenoses were overestimated (relative false-positives). One ICA occlusion was misdiagnosed when an ECA branch was misinterpreted as the ICA.

With the RP Doppler, $f_{50\%}$ bandwidths less than 1200 Hz were classified as indicating less than 25% diameter reduction, while 1200–1750 Hz represented 25–49% stenosis and greater than 1750 Hz predicted greater than 50% diameter reduction. Again, the absence of an ICA signal was felt to represent 100% occlusion (Table 5). In all, among the 81 vessels examined, there were 70 correct

TABLE 2. *Comparison of Continuous-Wave Doppler Power Frequency Spectrum Analysis Bandwidth at 50% of Peak Frequency ($f_{50\%}$) with Carotid Stenosis by Angiography*

Angiographic Stenosis (% Diameter)	$f_{50\%}$ Criterion	Sensitivity (%)	Specificity (%)	Accuracy (%)	Positive Predictive Value (%)	Negative Predictive Value (%)
10%	1600 Hz	93.8	90.6	92.9	96.2	85.3
25%	1800 Hz	92.0	94.7	92.9	97.2	85.7
50%	3200 Hz	92.9	91.6	92.0	86.7	95.6

predictions for an 86.4% accuracy. Five stenoses were underestimated, and six stenoses were overestimated, mostly in the 25–49% diameter reduction category. Also, one severe ICA stenosis (95%) was misdiagnosed as an ICA occlusion.

Similar selection methods were utilized to obtain the optimal threshold peak frequency cutoff values from the two respective Doppler techniques. Neither technique provided an acceptable value for the 10% diameter reduction category because of the overlap between f_{max} values from arteries with less than 10% stenosis and those with 10–49% stenosis. Utilizing the CW Doppler, peak frequencies found to best classify disease into the categories of greater or less than 25% and 50% stenosis were 3600 and 4500 Hz, respectively. The former f_{max} was 95% sensitive, 82% specific, and 90% accurate, while the latter f_{max} value was 98% sensitive, 78% specific and 85% accurate (Table 6). With the RP Doppler, peak frequencies of 2500 and 3000 Hz were best able to classify arteries into categories of greater or less than 25% and 50% stenosis, respectively. An f_{max} value greater than 2500 Hz predicted greater than 25% diameter reduction with 77% sensitivity, 92% specificity, and 87% accuracy. For the angiographic finding of 50% stenosis, the f_{max} value of 3000 Hz was 89% sensitive, 92% specific, and 92% accurate (Table 7).

Finally, 15 internal carotid arteries were classified correctly as totally occluded by both CW Doppler criteria and angiography. However, CW Doppler falsely predicted one ICA occlusion, since the vessel was only 35% stenotic, and one ICA occlusion was missed noninvasively, when an ECA branch was misinterpreted as a normal ICA. With the RP Doppler, eight ICA occlusions were classified correctly. However, one additional ICA considered occluded by RP Doppler was found to possess a high bifurcation with a 95% stenosis at the origin of the ICA. A patent lumen was neither visualized ultrasonically nor insonated with the Doppler sample volume. Also, only five of the original eight ICA occlusions would have been positively diagnosed by ultrasonic imaging alone. The image was normal in one case and was difficult to interpret in two others, because of nonhomogeneous plaques and arterial wall calcification with resultant acoustic shadowing.

Discussion

The detection of carotid arterial occlusive disease by direct noninvasive vascular techniques has become an important factor in the clinical management of cerebrovascular disease. Initially, only an audible interpretation of continuous wave bidirectional Doppler signals was available.[11] In an effort to quantitate the results, a frequency *versus* time gray-scale spectral analysis of the CW Doppler signals was developed. With this technique, Barnes et al. demonstrated a 98% sensitivity for detecting hemodynamically significant (50%) lesions.[1] Similar findings were reported by Brown et al.,[2] who identified 25% ICA stenosis with 91% sensitivity and 92% specificity. Recently, Krause et al.[3] performed PFSA to analyze carotid CW Doppler velocity signals. With the frequency bandwidth at 50% peak amplitude ($f_{50\%}$), a quantitative index of spectral broadening, all degrees of ICA pathology were identified with 91% accuracy. For hemodynamically significant lesions, their sensitivity was 100%. With subjective grading of spectral broadening, Brown et al.[2] demonstrated similar results.

Recently, ultrasonic imaging and associated RP Doppler spectrum analysis have been combined in the duplex

TABLE 3. *Comparison of Range-Gated Pulsed Doppler Power Frequency Spectrum Analysis Bandwidth at 50% of Peak Frequency ($f_{50\%}$) with Carotid Stenosis by Angiography*

Angiography Stenosis (% Diameter)	$f_{50\%}$ Criterion	Sensitivity (%)	Specificity (%)	Accuracy (%)	Positive Predictive Value (%)	Negative Predictive Value (%)
10%	350 Hz	97.7	97.5	97.6	97.7	97.5
25%	1200 Hz	80.7	98.1	91.7	96.2	90.0
50%	1750 Hz	94.4	93.9	94.0	81.0	98.4

TABLE 4. *Classification of Degrees of Carotid Stenosis with CW Doppler Bandwidth at 50% Peak Frequency ($f_{50\%}$) Compared with Angiography*

	CW Doppler PFSA $f_{50\%}$ (Hz)				
Angiographic Stenosis (% Diameter)	1800	1800–3200	3200	No Audible Doppler	Total
0–24	36	3			39
25–49	6	21	6		33
50–99		3	39		42
100				15	16
Total	42	28	45	15	130

TABLE 5. *Classification of Degrees of Carotid Stenosis with Range-Gated Pulsed Doppler Bandwidth at 50% Peak Frequency ($f_{50\%}$) Compared with Angiography*

	RP Doppler PFSA $f_{50\%}$ (Hz)				
Angiographic Stenosis (% Diameter)	1200	1200–1750	1750	No Audible Doppler	Total
0–24	14	1			42
25–49	5	4	4		13
50–99			17	1	18
100				8	8
Total	46	5	21	9	81

scanner. Blackshear et al.[4] demonstrated this technique to be 92% accurate for detecting lesions with 50% diameter reduction, and their findings were supported by Fell et al.,[5] Doorley et al.,[6] and Russell et al.[12] However, using subjective means of evaluating spectral broadening, these investigators had difficulty detecting the hemodynamically insignificant lesions that were less than 50% stenotic. Sheldon et al.[13] utilized the ratio of maximum to mean frequency at peak systole obtained from PFSA data to quantitate changes in spectral broadening and correctly identified all stenoses greater than 40% and all normal arteries (less than 20%). For 25% stenoses, their technique was 90% sensitive, 95% specific, and 95% accurate.

Doppler spectrum analysis has become the best available method for noninvasively diagnosing carotid arterial occlusive disease. The accuracy of most present techniques is based on peak frequency measurements and a subjective evaluation of spectral broadening. Peak frequency values (f_{max}) have been thoroughly analyzed and increase steadily with increasing severity of disease once a 50% diameter reduction level is reached. However, the sensitivity, specificity, and accuracy of peak frequency measurements decrease for less severe lesions. As seen in Figures 3 and 4, this deficiency is due to the overlapping values obtained from arteries with less disease.

Spectral broadening, a measure of flow disturbance and turbulence, proportionally parallels the increase in disease severity.[3,4,8,14] Recent reports suggest that the frequency bandwidth at $f_{50\%}$ is a quantitative measure of spectral broadening, which is found by performing PFSA on CW or RP Doppler frequency shift tracings.[3,8] This index provides information comparable to peak frequency data for stenotic lesions greater than 50% and also categorizes lesions less than 50% with greater than 90% accuracy.

When considering which method is more accurate in identifying carotid arterial disease, variables other than the test technique appear significant. The most prominent variable is the examiner, who can unintentionally bias the results and make one technique appear superior to another. To avoid this hazard, a single observer, blinded from each patient's angiographic findings, performed all of the examinations during the 15 months of this study.

The results of this study, utilizing PFSA to analyze CW and RP Doppler information, suggest that there is little difference in the ability of the two techniques to diagnose and categorize carotid arterial occlusive disease accurately. However, with $f_{50\%}$ analysis, the RP Doppler system was 1–3% better than the CW Doppler in all but one category of disease. When peak frequency analyses were compared, the CW Doppler was much more sensitive, while the RP Doppler was more specific.

Both methods predicted arterial occlusions with similar accuracy, although the duplex scanner, with its simultaneous Doppler and imaging capabilities, made this task easier. Still, over 90% of ICA occlusions were correctly diagnosed with the CW Doppler. Both techniques can err in the diagnosis of complete occlusion. With the CW Doppler, ECA branches may be mistaken for a normal ICA, while, using the RP Doppler system, a very tight stenosis can be misdiagnosed as an occlusion because the

TABLE 6. *Identification of Carotid Stenosis by Continuous-Wave Doppler Power Frequency Spectrum Analysis Peak Frequency (f_{max}) Compared with Angiography*

Angiographic Stenosis (% Diameter)	f_{max} (+) Criterion	Sensitivity (%)	Specificity (%)	Accuracy (%)	Positive Predictive Value (%)	Negative Predictive Value (%)
25%	3600 Hz	94.7	81.6	90.3	91.0	88.6
50%	4500 Hz	97.6	77.5	85.0	71.9	98.2

TABLE 7. *Identification of Carotid Stenosis by Range-Gated Pulsed Doppler Power Frequency Spectrum Analysis Peak Frequency (f_{max}) Compared with Angiography*

Angiographic Stenosis (% Diameter)	f_{max} (+) Criterion	Sensitivity (%)	Specificity (%)	Accuracy (%)	Positive Predictive Value (%)	Negative Predictive Value (%)
25%	2400 Hz	77.4	92.3	86.6	85.7	87.0
50%	3000 Hz	88.9	92.2	91.5	76.2	96.7

small Doppler sample volume may not identify the patent but minute vessel lumen. Both problems are equally serious, but infrequent.

The only major difference between the two Doppler methods studied was seen when angiographically determined stenosis was compared to the 50% frequency bandwidth. Linear regression analysis showed both techniques to possess a linear relationship; however, the correlation coefficient for the RP Doppler method was better than that for the CW Doppler (*i.e.,* RP Doppler predictions fell closer to the best fit line than those from the CW Doppler). This difference suggested a linear progression of stenosis in individual patients examined serially with the RP Doppler, while the CW Doppler suggested more erratic progression.

From this study, neither technique appears clearly superior. However, each method has its advantages and disadvantages, which have to be considered from the viewpoint of a particular type of application.

The continuous train of impulses encompassing the whole vessel diameter facilitates the search for the vessel and especially for the search for a very narrow and isolated stenosis. The continuous mode of operation, however, sometimes makes it more difficult to separate the desired signal from that originating from an adjacent vessel. The CW systems are generally much less expensive than the RP Doppler duplex systems.

The small sampling volume of the RP pulsed Doppler makes it possible to easily separate signals from other Doppler shifting sources and to analyze the velocity profile in the examined vessel by changing the gating of the signal. Both contribute to the increased accuracy of the measurement. On the other hand, the small sampling volume may make it difficult to locate an isolated stenosis without additional help from an imager. The usual combination of an RP Doppler with an imaging system is therefore highly advantageous.

Thus, either an RP Doppler system with a widely variable sampling volume or a combination of an (interswitchable) CW and RP Doppler system would be a most effective diagnostic tool for the carotid area.

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