

Examination of Carotid Arteries with Quantitative Color Doppler Flow Imaging

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The results of conventional duplex scanning were compared with QCDFI. A total of 224 consecutive patients comprising 442 unilateral carotid systems were examined by conventional duplex techniques. MPSV, as determined by QCDFI, were recorded for each of the 442 carotid segments and grouped according to the previously determined degrees of stenosis.

The predictive value of QCDFI was confirmed by angiography with an overall accuracy of 91%. Results obtained by duplex scanning correlated with angiography 89% of the time. Based on QCDFI data, a scale to grade carotid stenosis was developed. **KEY WORDS:** Carotid arteries; Color Doppler flow imaging; Duplex scanning.

The noninvasive evaluation of the extracranial carotid system has progressed considerably in the past two decades. The combination of B-mode ultrasonography and pulsed Doppler spectral analysis has allowed the clinician both to visualize the anatomy of accessible blood vessels and to assess the blood flow velocity within vessels at various stages of the cardiac cycle. Duplex scanning of the extracranial carotid system has become a standard noninvasive test, and, within the past several years, duplex scanners have been further enhanced by the introduction of color

flow Doppler capabilities. In this way, criteria have been developed to predict the percent diameter reduction in patients with carotid disease based on the morphologic and hemodynamic data obtained in the extracranial carotid system.

Conventional duplex scanning involves the use of a fast Fourier transform to analyze returning pulsed Doppler signals. The velocities of a specific population of blood cells at a particular time and in a predetermined volume (gate) in the carotid artery are determined and displayed. Color flow Doppler imaging typically employs an autocorrelative method to analyze similar returning pulsed Doppler signals. Rather than display individual velocities of blood cells at a location and time, mean velocities of grouped blood cells pulsating past multiple sampling sites in the transducer beam are determined as pixels.¹ The various mean velocities are each assigned a color and displayed on the monitor as the familiar color flow.²

To date, the main advantage of color flow Doppler imaging has been to facilitate the location and interrogation of blood vessels by the technologist. Areas of turbulent flow within a vessel, often associated with stenotic lesions, or complete absence of flow, found in occluded segments of vessels, often can be

ABBREVIATIONS

QCDFI, Quantitative color Doppler flow imaging; MPSV, Mean peak systolic velocities; PSV, Peak systolic velocities

Received June 4, 1993, from The Vascular Blood Flow Laboratory, The Graduate Hospital (C.C.B., M.S.W., M.C.), and The Vascular Laboratory, Germantown Hospital Medical Center, Philadelphia, Pennsylvania (P.F.S.). Revised manuscript accepted for publication September 9, 1993.

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detected first by changes in color flow. Spectral analysis of a specific sample volume can then be done. Clinical trials have confirmed that color flow Doppler imaging has improved the accuracy and speed of duplex scanning.³ The main role of color flow Doppler imaging, therefore, has been as an adjunct to duplex scanning. Color flow Doppler imaging can also be used to measure the mean velocity of blood flow at multiple sites within a vessel during various stages of the cardiac cycle. These values can then be compared to velocities of blood flow obtained similarly by pulsed wave spectral analysis. In this way, color flow Doppler imaging becomes an independently employed, quantitative device. It is the purpose of this study to compare numerical velocity data obtained by QCDFI with velocities obtained by spectral analysis in the prediction of carotid stenosis.

MATERIALS AND METHODS

Two hundred twenty-four patients referred to the Vascular Blood Flow Laboratory for evaluation of the extracranial carotid circulation were included in this study. The mean age of the patients studied was 69 years, with a range of 34 to 91 years. One hundred eleven patients were women and 113 were men. Patients included in the study were entered on a consecutive basis over a 1 year period and included both inpatients and outpatients. In all cases, carotid imaging was ordered by a referring physician either for routine screening or for evaluation of specific neurologic symptoms and was in accordance with institutional guidelines. Four hundred forty-two unilateral extracranial carotid arteries were examined. Six patients were not imaged bilaterally because of poor positioning or compliance, or both.

Imaging of the extracranial carotid circulation was performed with two duplex scanners, the Acuson 128 and the Acuson 128XP (Acuson, Mountain View, CA). Both units used identical software in analyzing Doppler velocimetry data. All imaging was performed with a 5 MHz probe. Studies were recorded on a Panasonic VHS videotape and interpreted forthwith.

A series of spectral analysis measurements were conducted at selected points within the extracranial carotid vasculature. First, the PSV were measured in areas of nonturbulent flow proximal to the carotid bifurcation using a 1.5 mm gate. Next, PSV at specific sites within the internal carotid artery were found using a 1.5 mm sampling gate. Sample sites were selected in areas of suspected internal carotid artery stenosis as suggested by either B-mode imaging or "jet streams" seen using color flow Doppler imaging

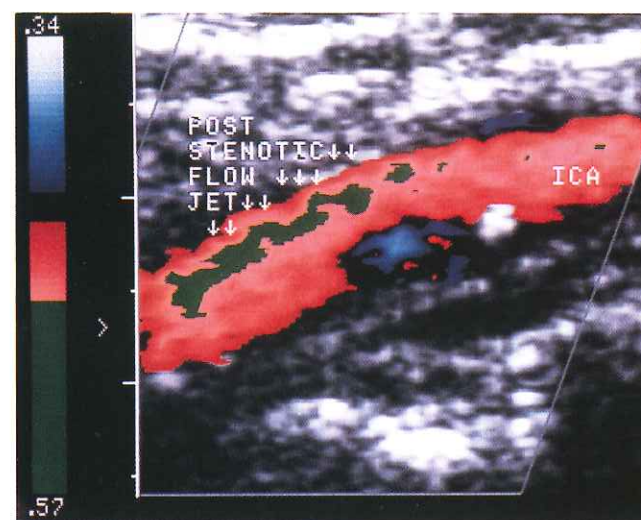


Figure 1 Selection of sample sites using "jet streams" visualized by color flow Doppler imaging.

(see Fig. 1). The PSV recorded was the maximal PSV measured at the area of concern. If no area of stenosis could be found, a midstream sample in the proximal portion of the internal carotid artery was taken using a 1.5 mm gate. All measurements were corrected to an angle of 64 degrees or less. Concurrently, color flow Doppler images were recorded on videotape in the same carotid segments as above. Multiple consecutive MPSV were measured over an 8 second interval with a color Doppler capture function available on the scanners used. The color Doppler capture function displayed the highest mean velocity by activating color picture elements as they appeared on the screen. Once displayed, a color pixel would remain on-screen until a subsequent mean velocity sample, at the same point and of greater magnitude replaced it. In all cases the color Doppler mean velocity samples were taken parallel to streamline flow and the angle corrected to 64 degrees or less. The highest MPSV was more effectively visualized with an off-color tagging function also available on the scanners used (Fig. 2). This method of sampling ensured that the highest MPSV at a specific site was obtained (Fig. 3). Spectral analysis and B-mode imaging data were used to place the 338 carotid segments into six different categories of stenosis: normal (0%), mild (1-39%), moderate (40-59%), severe (60-79%), critical (80-99%), and occluded (100%). Normal (0%) was indicated if the MPSV and mean internal carotid artery to common carotid artery velocity ratio fell within appropriate limits and a clearly demarcated flow reversal component was visualized within the carotid sinus.⁴ Minor (1-59%) and hemodynamically significant (60-99%) stenoses were diagnosed if the ob-

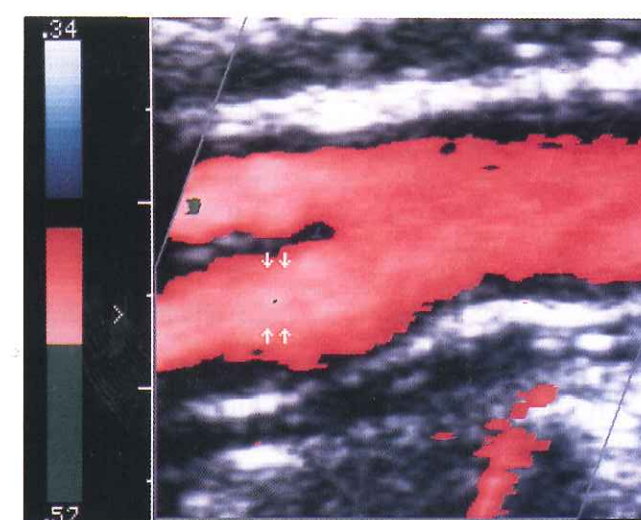


Figure 2 Highest MPSV in the internal carotid artery visualized with the off-color tagging function.

served hemodynamic configurations around lesions during color duplex scan showed a flow jet containing appropriate MPSV and mean internal carotid artery to common carotid artery velocity ratio values and a mottled, "mosaic" turbulence distally.⁵ Finally, occlusion (100%) of the internal carotid artery was indicated by an absence of color flow within the internal carotid lumen and by excessively low velocity bursts of reversed flow resulting from cranial reverberation (Fig. 4).

A constant (K) was determined by comparing the MPSV of the internal carotid (ic) artery found using QCDFI with the PSV of the internal carotid artery found using conventional pulsed wave Doppler im-

Figure 3 Sampling of the highest MPSV within the internal carotid artery.

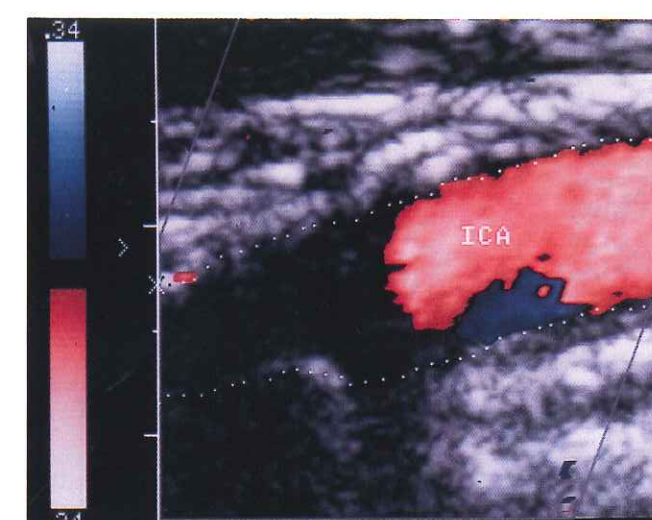
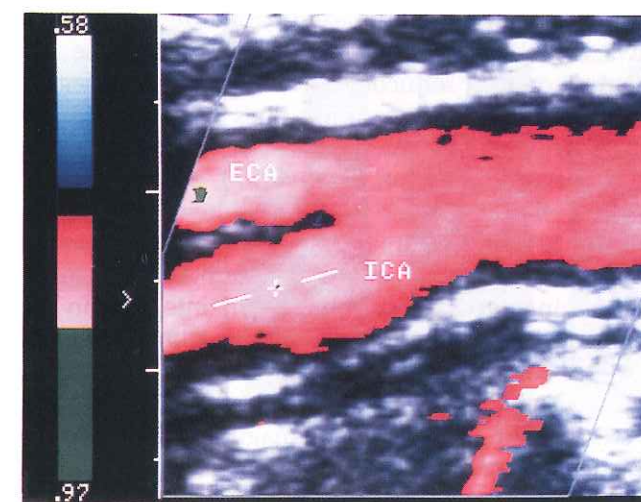


Figure 4 Occlusion of the internal carotid artery as indicated by color Doppler flow imaging.

aging (i.e., $K = \text{MPSV}_{\text{ic}}/\text{PSV}_{\text{ic}}$). A different value of K was averaged for each category of stenosis as measured by spectral analysis and B-mode imaging.^{6,7} The K scale was used to more easily compare PSV and MPSV values and subsequently as a basis in determining QCDFI criteria to evaluate carotid stenosis. QCDFI criteria were assembled relative to previously established standard Doppler velocity criteria.⁸⁻¹¹

Twenty-three of the 224 patients in this study group underwent intra-arterial digital subtraction angiography of the extracranial carotid circulation at the discretion of the physician in charge of the patient. A total of 46 extracranial carotid segments were evaluated by angiography. Percent stenosis was measured by a vascular radiologist unaware of the results of the QCDFI scanning technique. Only patients stated as having operable lesions were referred to carotid angiography. The vascular radiologist was unaware of the exact diameter stenosis determined by the conventional Doppler technique when rendering an impression of corresponding angiograms. Angiographic results revealing carotid disease with less than a critical reduction in diameter were incidentally found in patients being examined for significant contralateral lesions. The imaging itself was performed by three registered vascular technologists, each of whom had at least 2 years of experience. Color Doppler MPSV values were determined prior to measuring PSV by using spectral analysis so as not to bias the technologist. As results of duplex scanning are highly technician-dependent, the above protocol as to sampling site and technique was strictly followed to further control interrater bias.

Table 1: Standard Spectral Analysis versus QCDFI in Ascertaining the Level of Carotid Artery Disease

QCDFI (% Stenosis)	Standard Spectral Analysis (% Stenosis)					
	0	1-39	40-59	60-79	80-99	100
0	55	0	0	0	0	0
1-39	0	231	3	4	0	0
40-59	0	14	19	3	0	0
60-79	0	3	1	52	5	0
80-99	0	0	0	2	36	0
100	0	0	0	0	0	24

RESULTS

Analysis by both QCDFI and conventional spectral imaging placed 12% of unilateral carotid systems into category 1, normal. The average PSV of the internal carotid artery for this group was 57.80 cm/s, with a range of 33 to 90 cm/s. The average MPSV for this group was 51.98 cm/s, with a range of 28 to 89 cm/s. The *K* value for category 1 was equal to 0.90. Fifty-six percent of unilateral carotid systems were classified as mild stenosis (category 2) by spectral analysis and 55% by QCDFI. The average PSV of the internal carotid artery for this group was 71.27 cm/s, with a range of 27 to 119 cm/s. The average MPSV for this group was 60.98 cm/s, with a range of 29 to 110 cm/s. The *K* value for this category was equal to 0.86. Six percent of unilateral carotid systems fell into category 3 by spectral analysis, and 8% were classified as moderate stenosis by QCDFI. The average PSV of the internal carotid artery for this group was 123.50 cm/s, with a range of 107 to 172 cm/s. The average MPSV for this group was 97.61 cm/s, with a range of 74 to 150 cm/s. The *K* value for category 3 was equal to 0.79. Category 4, severe stenosis, was 12% of the sample space for both modalities. The average PSV of the internal carotid artery for this group was 186.33 cm/s, with a range of 136 to 246 cm/s. The average MPSV for this group was 144.08 cm/s, with a range of 110 to 222 cm/s. Correspondingly, the *K* value for this category was equal to 0.77. Eight percent of the 338 unilateral carotid systems fell into category 5 via spectral analysis, and 9% were shown to be critical stenoses with the QCDFI method. The average PSV of the internal carotid artery for this group was 396.90 cm/s, with a range of 251 to 759 cm/s. The average MPSV for this group was 273.32 cm/s, with a range of 160 to 470 cm/s. The *K* value for category 5 was equal to 0.74. Finally, 5% were classified as occluded (category 6) and thus produced no velocimetry data (see Table 1).

From this information, QCDFI criteria to assess internal carotid artery disease were established as a modification of previous conventional criteria. Based

on MPSV values sampled within the internal carotid artery and MPSV ratios of the internal to common carotid arteries, the QCDFI criteria read similarly to the conventional Doppler criteria from which they were formed (see Table 2). Theoretical trials confirm the relationship between PSV and MPSV values as a linear decrease in *K* with increasing percent stenosis.¹² The *K* values ascertained by our study confirm this trend and are similar in trend to those proposed theoretically (see Table 3). A comparison of angiography to duplex scanning in the 23 patients that underwent intra-arterial angiography in our facility showed an accuracy of 89% in diagnosing hemodynamically significant lesions, with a positive predictive value of 100% and a negative predictive value of 77%. Similarly, in comparing the 23 intra-arterial angiograms to the QCDFI technique on the same subjects, an overall accuracy of 91% was calculated, with positive and negative predictive values of 100 and 82%, respectively (see Table 4).

DISCUSSION

Spectral analysis enables the technologist to measure the velocity of moving red blood cells in the carotid artery at different points in the cardiac cycle. Combining these velocity data with B-mode imaging allows the clinician to subdivide carotid disease depending on flow reduction and, therefore, the degree of stenosis. Duplex scanning does not allow for simultaneous measurement of hemodynamic and anatomic data in real time, however.

Color flow Doppler imaging, when used as an adjunct to duplex scanning, increases the accuracy of duplex evaluation of the carotid system.¹³ Color Doppler imaging superimposes hemodynamic data on the anatomic B-mode scan and therefore allows the clinician to correlate morphologic findings with their hemodynamic effects in real time. For the carotid system, color flow Doppler imaging quickly distinguishes the external carotid artery from the internal carotid artery as well as velocity changes due to ves-

Table 2: Standard Pulsed Wave and Quantitative Color Doppler Criteria for Evaluating Carotid Artery Disease

Diameter Stenosis (Category)	PSV (cm/s)	PSV Ratio (ICA/CCA)	MPSV (cm/s)	MPSV Ratio (ICA/CCA)
0% (Normal)*	< 110	< 1.80	< 90	< 1.40
1-39% (Mild)	< 110	< 1.80	< 90	< 1.40
40-59% (Moderate)	< 130	< 1.80	< 110	< 1.40
60-79% (Severe)	> 130	> 1.80	> 110	> 1.40
80-99% (Critical)	> 250	> 3.70	> 190	> 2.70
100% (Occlusion)	NA	NA	NA	NA

*In addition to other indicators

NA, Not applicable; ICA, internal carotid artery; CCA, common carotid artery.

sel kinking or tortuosity. The absence of flow in occluded segments can be more readily seen, and the direct effects of a stenotic or ulcerative plaque on blood flow can be visualized concisely in real time. In vessels with significant stenosis, color flow Doppler imaging gives a more precise location and direction of jet stream flow and therefore facilitates spectral sampling of that area.

Color flow Doppler imaging alone has been used in the assessment of carotid disease. Criteria for determining percent stenosis have been based on semi-

quantitative data.¹⁴ Color changes in stenotic and poststenotic areas of the common and internal carotid arteries at various stages of the cardiac cycle are used to determine the percent stenosis.¹⁵ The data reported in this study have attempted to classify the percentage of stenosis based upon quantitative data obtained by color flow Doppler imaging. The results obtained provide a grading system of flow reduction for the carotid arterial tree based solely on QCDFI.

The results obtained through QCDFI have proven comparable to color flow assisted duplex scanning in

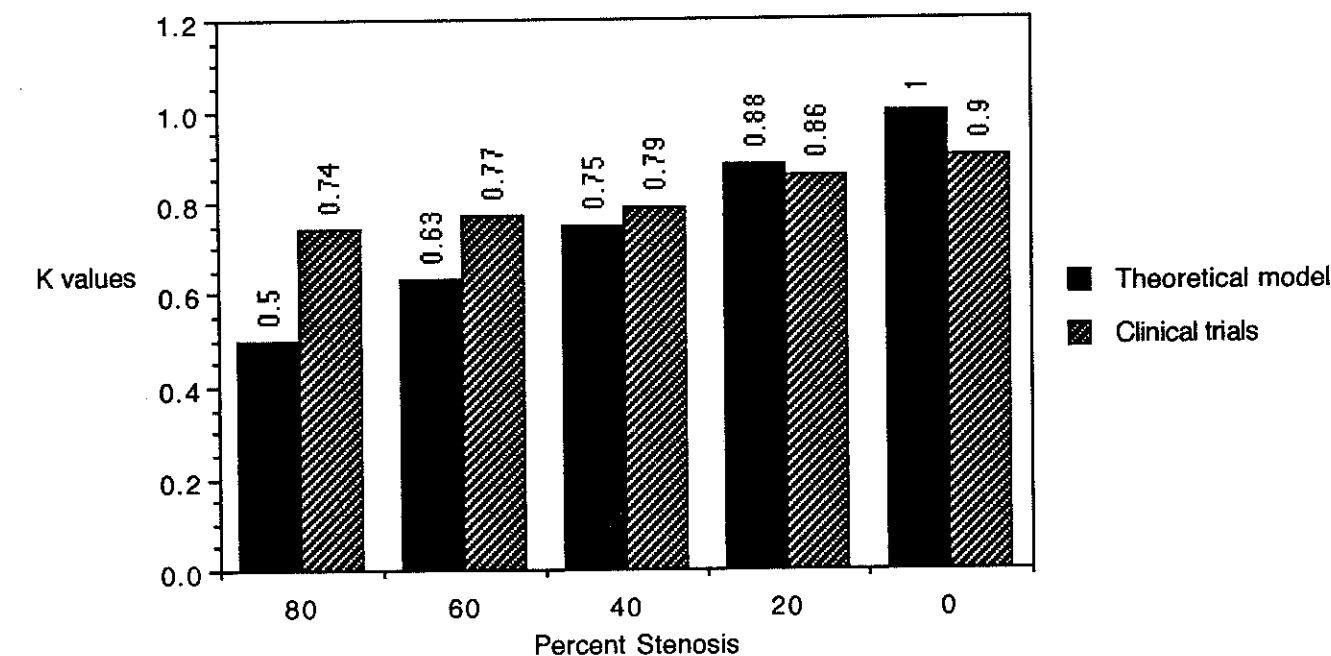
Table 3: Comparison of Constants Relating Spectral Doppler and QCDFI Analyses Theoretically and Clinically

Table 4: Intra-Arterial Angiography versus Standard Spectral Sonography and QCDFI in Ascertaining the Level of Carotid Artery Disease

Standard Doppler (% Stenosis)	Arteriography (% Stenosis)					
	0%	1-39%	40-59%	60-79%	80-99%	100%
0%	0	0	0	0	0	0
1-39%	0	12	1	0	0	0
40-59%	0	2	2	0	0	0
60-79%	0	2	1	5	2	0
80-99%	0	0	2	0	9	0
100%	0	0	0	0	0	8
QCDFI						
(% Stenosis)						
0%	0	0	0	0	0	0
1-39%	0	13	0	0	0	0
40-59%	0	1	3	0	0	0
60-79%	0	2	1	3	3	0
80-99%	0	0	2	2	8	0
100%	0	0	0	0	0	8

Boldface numbers indicate ?.

the detection of carotid stenosis. This has been corroborated in some cases by angiography. The accuracy of this technique can be attributed to the ability of QCDFI to display both the anatomic and hemodynamic information simultaneously. Furthermore, the ultrasonographer has the benefits of spatial orientation as well as a precise velocity indicator in the same field of view when using QCDFI. Little time is spent searching for the point of highest velocity as it becomes evident with an off-color velocity indication function that can be manipulated to isolate the highest velocity in a stenotic jet. In software systems containing an angle correction feature, the color Doppler display produces information about the actual currents and eddies moving past a stenosis. Consequently, the diagnostician has a precise indicator of what angle to correct to promote a more accurate velocity reading.^{16,17} Flow jets and their direction may be seen in relationship to the entire vessel being investigated, allowing for more consistent angling of the postprocessed color Doppler velocity sample. Furthermore, pixel analysis inherent to QCDFI provides a more accurate sample placement than conventional duplex scanning. The sample of blood cells contained in a pixel when imaged in real time at the point of highest MPSV in a flow jet will better isolate the hemodynamic effects of a stenosis than the spectral analysis sample taken out of real time.

Thirty-five subjects produced disease classifications that did not match between conventional and QCDFI methods. Possible explanations include transient cardiac changes occurring between the two

readings, slight variations in transducer placement, or intraclinician error. Similar sources of error, as well as interrater variation, may have contributed to discrepancies between the Doppler assessments and angiographic results. Spuriously increased or decreased velocities related to persistent cardiac abnormalities, contralateral carotid artery disease, or tandem lesions would be expected to affect both methods in the same way.

In an effort to proceed one step further in the evolution of color Doppler imaging, this study has retrospectively attempted to evaluate the carotid system through a more quantitative method of color Doppler analysis. These additional insights that the clinician has when using QCDFI over standard Doppler sonography may account for the increase in the color method's overall accuracy and are distinct benefits unique to the QCDFI system.

The frequency of noninvasive Doppler ultrasonographic scanning has increased considerably as the prevalence of asymptomatic patient groupings with significant carotid artery disease come before the vascular specialist.¹⁸ Internal carotid endarterectomy is once again emerging as a valid and safe prophylactic option for the patient with diseased carotid arteries.^{19,20} With these changes in mind, the presently accepted methods of noninvasive Doppler detection for carotid disease can be supplemented with color Doppler imaging and improved by QCDFI.²¹ As the technology of color Doppler imaging progresses, the accuracy and availability of QCDFI will become more widespread and greatly improved.²² Applications to

other anatomic sites such as arterial bypass grafts, renal allografts, intracerebral shunts, and abdominal vasculature are possible.²³⁻²⁵ Consequently, QCDFI may be employed as a reliable means of evaluating the extent of extracranial carotid atheromatous pathologies. It also provides an alternative method that may prove advantageous in certain difficult situations where conventional spectral analyses may be less effective or in need of supplemental information.

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