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Carotid Atherosclerosis: High-Resolution Real-Time Sonography Correlated with Angiography

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The merits of high-resolution real-time sonography in detection of plaque and estimation of stenoses were compared with angiography in 97 carotid bifurcations from 50 consecutive patients. For flow-reducing lesions, that is, stenosis ≥50% or complete occlusion, sonographic accuracy was 86% and the mean difference in percentage narrowing was 17% (SD, 21.6%). For detection of normal or non-flow-reducing lesions, that is, <50% stenosis, sonographic accuracy was 89% and the mean difference in percentage narrowing was 8% (SD, 10.2%). Errors occurred mainly in severely diseased vessels and were often related to calcification in lesions and/or plaque of low echogenicity. Accuracy was lowest in predicting complete vessel occlusion (36%). Greatest accuracy was found in assessment of minimal disease. The technique is a useful supplement to the battery of noninvasive tests used to screen patients at risk for stroke and in defining those requiring angiography before surgery.

Carotid arteriography is the definitive investigative procedure for the assessment of patients with cerebral or ocular transient ischemic attacks (TIAs) who are considered for endarterectomy of the extracranial carotid arteries. However, there is difficulty in identifying patients with true TIAs from among the many presenting with vague neurologic symptoms, fainting attacks, dizzy spells, and the like. The contribution of noninvasive screening tests to the identification of extracranial carotid disease and more rational selection of patients for angiography has been emphasized [1]. Direct visualization of the neck vessels by high-resolution real-time sonography is one of the newest of these methods, and its use for identification of atheromatous plaques has been documented [2–6]. With the exception of a review by Zweibel [6], few details have been reported of the scanning technique, the variety of appearances observed in normal and abnormal vessels, and the accuracy of estimation of stenotic lesions. This report outlines our experience with carotid real-time scanning during a 2½ year period and compares in detail a group of 50 consecutive patients who underwent sonography and carotid angiography.

Materials and Methods

Most patients referred to our sonographic laboratory for carotid examination give a definite or suggestive history of TIAs. Fewer patients have a history of stroke, asymptomatic neck bruit(s), hypercholesterolemia, or are elderly or arteriosclerotic subjects considered at risk for stroke in connection with anticipated open heart surgery or another major surgical procedure.

For comparison of carotid sonography with angiography, the studies of 50 consecutive patients who underwent both procedures during the same hospital admission were reviewed. Only patients who had both tests within a 72 hr period were included in the study group. The sonographic data were examined without prior knowledge of the angiographic findings or clinical data. Both cervical carotid bifurcations were examined by sonography in all 50 patients. Forty patients had selective common carotid arteriography. Bilateral

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anteroposterior (AP) and lateral films of the carotid vessels in the neck were obtained in 37 patients and unilateral studies in the other three. The remaining 10 patients had nonselective carotid arteriograms obtained by filming the neck during biplane arch aortography in right and left posterior oblique projections. Thus, there were 97 separate carotid bifurcations examined by arteriography and available for comparison with the sonograms.

A high-resolution real-time sonographic scanner (Biosound) was used. It has an 8 MHz transducer housed in a self-contained water bath. An oscillating mirror focuses and directs the sonographic beam out of the transducer face, which consists of a flat membrane of 1.5 × 3.5 cm. The head of the transducer weighs about half a kilogram and can be readily manipulated while in contact with the skin to produce small changes in beam direction. The field of view is 4 cm in depth and 3.5 cm in width. Axial resolution is 0.3 mm in the focal zone, the position of which can be varied by means of a control between three separate fixed points located in the near, mid, and far fields of the image. The time gain setting of the instrument is maintained at a high level just short of that at which the image becomes degraded by noise artifacts. This is to allow detection of plaque of low echogenicity in the carotid arteries. The image is viewed in real time on a 9 inch (22.9 cm) television monitor and recorded on videotape. Hard-copy images are obtained on radiographic film with a multiformat camera.

The studies that form the basis of this report were performed without the benefit of simultaneous hemodynamic data. More recently, however, range-gated pulsed Doppler with a 1 mm^3 adjustable volume sampler has been incorporated into our system. This enables flow characteristics within imaged vessels to be studied by means of audio signals.

Optimal and stable positioning of the head and neck during scanning was essential to allow systematic examination of the common carotid artery, its bifurcation, and the proximal internal carotid and external carotid branches. A dental chair with the headrest removed was found to be ideal for this purpose. The height of the chair and the slope of its backrest are adjustable. The patient is seated semierect with the neck extended. The head is turned away from the side to be examined and rests on a small pad on the top of the backrest. The operator sits behind the patient and passes his arms on either side of the patient's neck to support the transducer in front. The television monitor, placed to one side of the chair, is easily viewed by the operator over the patient's shoulder. We prefer the semierect to the supine position because it allows more flexibility in scanning the vessels in different planes, especially when tracing their long axes high in the neck. In the erect position, there is no engorgement of neck veins and the tissues around the vessels are less bulky. The imaged internal jugular vein, being collapsed, is thus less likely to be confused with an artery. The common carotid is examined first, in the longitudinal plane, beginning near the medial end of the clavicle. Its course is then followed upward to the bifurcation. The branch vessels are next examined and followed as high as possible in the neck. The arteries are then viewed in cross section by rotating the transducer through 90° and retracing their course. Particular attention is given to scanning the bifurcation region in two longitudinal projections, at about right angles to one another, to ensure detection of eccentric plaque. When diseased areas are identified, they are scanned in several longitudinal projections. If scanned in only one longitudinal plane, error in assessment of the degree of stenosis may occur due to asymmetry of thickness of the vessel wall at different points on its circumference [6].

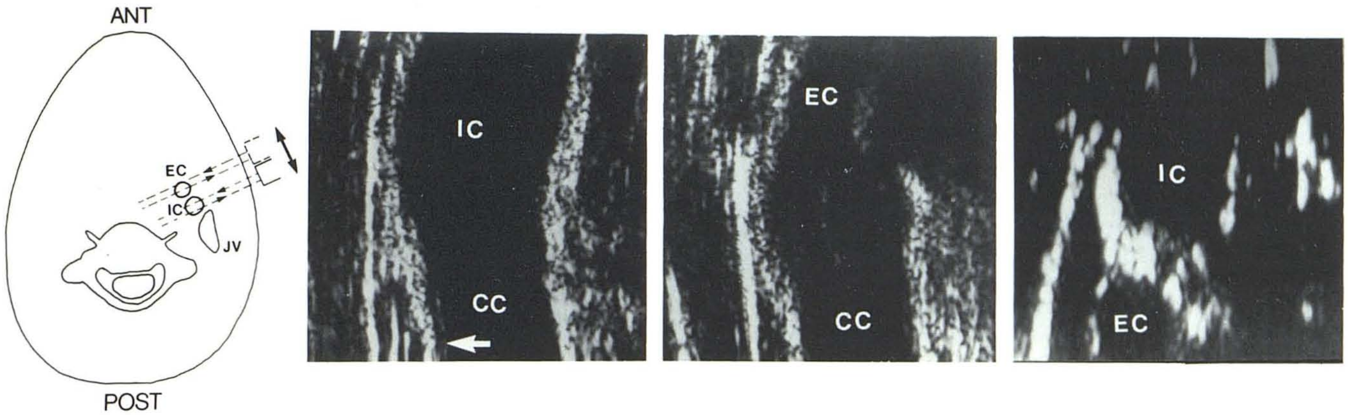
In comparing sonography and angiography, only disease at the carotid bifurcation and the immediately adjacent parts of the common and internal carotid arteries was considered. Localized intimal thickening of 1 mm or more was regarded as an indication of plaque at this site. Similarly, localized narrowing of 1 mm or more at angiography was taken to be an indication of plaque. Measurements of the vessel lumen in the contiguous common and internal carotid segments were made to the nearest millimeter and images showing the narrowest dimension at both sonography and angiography were selected for this purpose. Calipers were used to obtain measurements directly from the angiographic films. For sonography, measurements were taken directly from the television monitor by means of an integral electronic calibrated graticule. This can be superimposed on the image by means of an instrument control. To calculate the percentage diameter reduction of the lumen at sites of stenosis, measurements were also obtained of the diameter of the internal carotid artery beyond the diseased segment.

Due to low confidence in detection of ulceration at sonography, no attempt was made to compare the accuracy of its detection by the two methods. Similarly, no attempt was made to correlate findings of ulceration at sonography with surgical findings. Because of the collapsed and deformed nature of specimens obtained at carotid endarterectomy, neither did we correlate estimates of stenoses with surgical findings.

Results

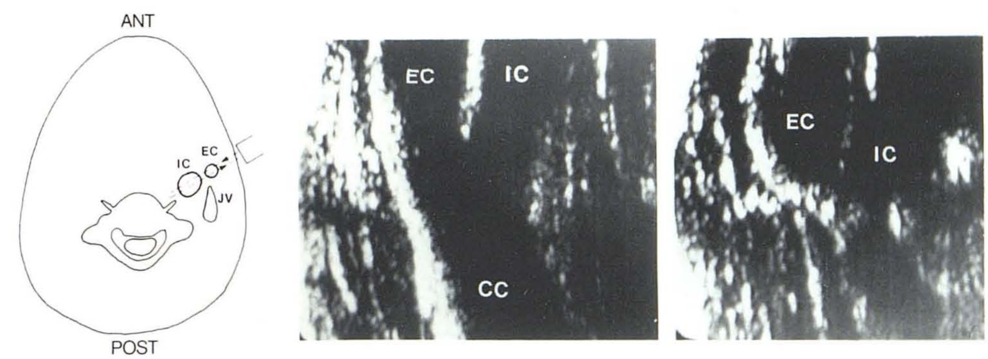
The common carotid artery was readily identified at the root of the neck in all patients and easily followed cephalad to the carotid bulb. This appeared as a slight increase in caliber of the lumen over 1–2 cm (fig. 1). A fine linear reflection was often observed paralleling the walls of the arteries. This, we believe, is due to specular reflections from the blood/intima interface and not a sign of abnormality since it is seen in normal subjects. It was separated by less than 1 mm from the more echogenic combined media and adventitia of the vessel wall in normal arteries (figs. 1 and 3). The internal carotid was usually found to assume a more direct continuation of the common than the external carotid. In 85%–90% of patients, the plane through the long axis of the internal and external carotid branches lay about parallel to the skin surface and simultaneous imaging of the two vessels was not possible (fig. 1). The identification of the two vessels was usually straightforward. The external branch lay in an anteromedial position and was smaller in caliber. On occasion, the origin of the superior thyroid artery could be identified arising from the external carotid. The internal carotid was usually the larger of the two vessels and maintained a close relationship to the internal jugular vein located in a lateral or posterolateral position. In 10%–15% of patients, the external carotid lay anterolateral to the internal carotid and the two could then be imaged simultaneously (fig. 2). In 30% of patients, the carotid bifurcation was at the C4 level or above at angiography. It was then more difficult to examine because movement of the transducer was obstructed by the angle of the mandible. In these circumstances, it was found that scanning from a posterolateral position, behind the angle of the mandible, usually provided adequate demonstration of the vessels in the upper neck. In this position, however, the internal carotid lay superficial to the external carotid in relation to the transducer. This was the reverse of their usual arrangement when scanned from the anterior approach.

At times, the course of the internal carotid turned abruptly posteriorly, cephalad to the bifurcation, and much manipu-



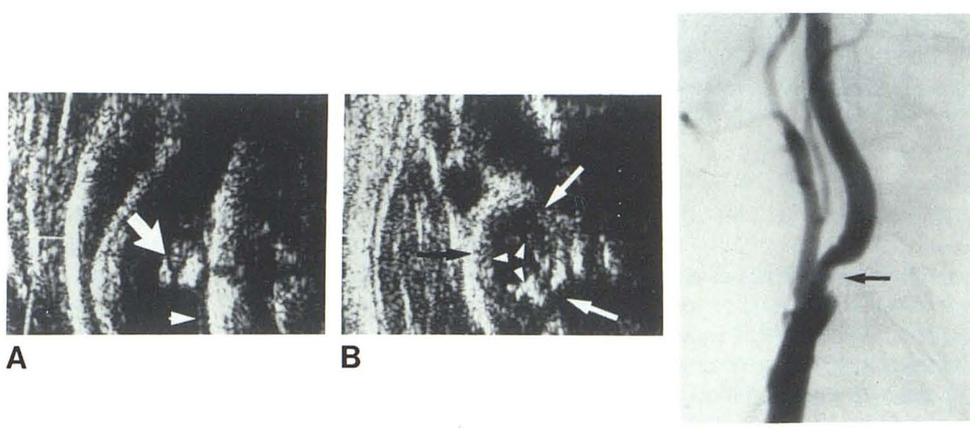
A B C D

Fig. 1.—Normal carotid bifurcation. **A**, Usual arrangement of carotid bifurcation branches relative to scanning plane, for example, external carotid artery (EC) is anteromedial to internal carotid (IC) and both vessels cannot be imaged simultaneously in their long axes. **B**, Carotid bulb in long axis at origin of internal carotid. Normal intimal surface echo (*arrow*). CC = common carotid artery. **C**, Smaller caliber external carotid artery in long axis arises from common carotid. **D**, Both vessels side by side in cross section. Skin line is to the left of the image in each case.



A B C

Fig. 2.—Normal carotid bifurcation. **A**, Normal variation of carotid bifurcation with external carotid artery (EC) lying anterolateral to internal carotid (IC). Scanning plane passes through long axes simultaneously. **B**, Common carotid artery (CC) and its bifurcation branches in long axis. **C**, Bifurcation branches in cross section with external carotid lying superficial to internal carotid.



A B C

Fig. 3.—Atheromatous plaque at the carotid bifurcation. **A**, Long axis image of common and internal carotid segments. Localized filling defect on deep wall of vessel (*arrow*). Lesion has areas of high and low echogenicity. Normal intimal surface echo in distal common carotid is just proximal to plaque (*arrowhead*). **B**, Cross sectional view at level of lesion shows its circumferential extent. Outer margins of vessel (*arrows*) and size of residual lumen (*arrowheads*) can be identified. *C*, Carotid angiogram. Plaque is seen as filling defect on posterior wall of proximal internal carotid artery (*arrow*).

lation of the transducer was needed in tracing it higher in the neck. Scanning the vessels in cross section was found of value in identifying their relationship to each other and provided orientation for scanning in the longitudinal plane (figs. 1 and 2). The internal jugular vein usually appeared as an oval or flattened structure superficial and posterior to the common and internal carotid arteries. Its caliber varied with respiration and position of the head. The vein could be

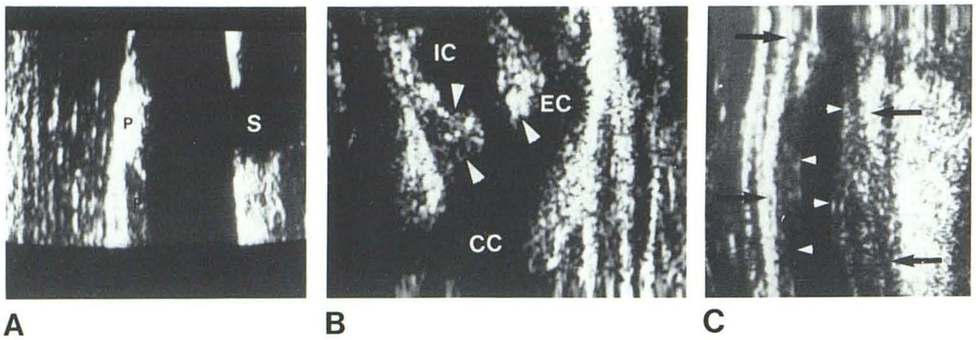


Fig. 4.—Differing sonographic appearance of atheromatous plaque. **A**, Long flat plaque (P) on superficial wall of vessel has highly echogenic distal extent. Deep surface of vessel at this level and adjacent structures not imaged because calcification in plaque causes acoustical shadowing (S). **B**, Plaque of intermediate echogenicity at origin of internal carotid (IC) (*arrowheads*) produces stricture at mouth of vessel. External (EC) and common (CC) carotid arteries. **C**, Long flat plaque of relatively low echogenicity on both superficial and deep walls of common carotid. Outer margins of vessel (*arrows*) and narrowed residual lumen (*arrowheads*).

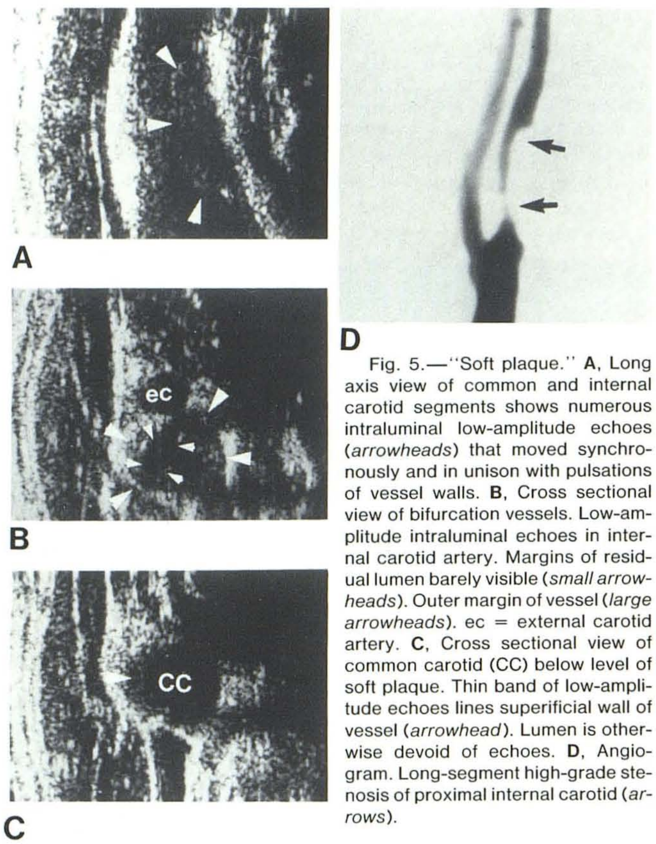


Fig. 5.—"Soft plaque." **A**, Long axis view of common and internal carotid segments shows numerous intraluminal low-amplitude echoes (*arrowheads*) that moved synchronously and in unison with pulsations of vessel walls. **B**, Cross sectional view of bifurcation vessels. Low-amplitude intraluminal echoes in internal carotid artery. Margins of residual lumen barely visible (*small arrowheads*). Outer margin of vessel (*large arrowheads*). ec = external carotid artery. **C**, Cross sectional view of common carotid (CC) below level of soft plaque. Thin band of low-amplitude echoes lines superificial wall of vessel (*arrowhead*). Lumen is otherwise devoid of echoes. **D**, Angiogram. Long-segment high-grade stenosis of proximal internal carotid (*arrows*).

identified by collapse of its lumen with gentle pressure of the overlying transducer or if direct visualization of blood flow was observed within its lumen. No intimal shadow was observed similar to that seen in the arteries.

Atheroma was identified as echogenic material encroaching into the arterial lumen (fig. 3). It was most frequently found on the posteromedial wall of the common and internal carotid segments. Large plaques were often circumferential and asymmetric in thickness, which was best shown in transverse section (figs. 3 and 5). Plaques exhibited much variation in size, surface configuration, and echogenicity (fig. 4). Highly echogenic foci were often associated with acoustic shadowing, presumably related to calcification. Location of such foci in the superficial wall of the vessel often caused partial obliteration of the sonographic beam. This caused obscuration of the lumen and far wall of the vessel. Plaques of low echogenicity were a common finding and frequently associated with extensive disease (fig. 5). Plaques of intermediate echogenicity were often found in the distal common carotid and occasionally extended over several centimeters (fig. 4C). Complete occlusion was indicated by intraluminal echoes without a discernible lumen (fig. 6) or by absence of pulsation of the vessel walls. Absence of pulsation was also seen in several vessels beyond a tight stenosis, however, and one totally occluded vessel showed transmitted pulsation from an adjacent patent external carotid artery. This appeared as movement of the entire vessel compared with the distensile pulsation seen in patent vessels. In a few instances, we were able to correlate sonographic findings with those at operation for carotid endarterectomy. Gross ulceration of plaque was anticipated from the sonograms in three patients. This was based on the appearance of marked irregularity of the intimal surface. Other features noted in these cases were abrupt discontinuity of the surface intimal shadow near the edge of an ulcer and well defined anechoic defects within plaque. The latter sign was seen when the ulcer was viewed en face (fig. 7).

Assessment of the degree of stenosis is shown in table 1 and figure 8. It was assumed that a flow-reducing lesion was one in which the stenosis was $\geq$50% or which caused complete occlusion. A non-flow-reducing lesion was considered to be one that reduced the diameter of the vessel by <50%. The accuracy of sonography in detecting flow-reducing lesions was 86% and that for detecting normal or non-flow-reducing lesions 89%. Sonography identified complete vessel occlusion in only four of 11 instances, which represents an accuracy of only 36% in the distinction between tight stenosis and occlusion. However, sonography was more successful than angiography in detection of minimal disease, and plaques were found in 10 of 19 vessels interpreted to be normal by angiography. These were small localized areas of intimal thickening of 1–3 mm. They were not appreciated at angiography due to their small size and smooth surface contour, which blended with the margins of the adjacent normal vessel wall.

Estimates of the degree of stenosis are presented in a

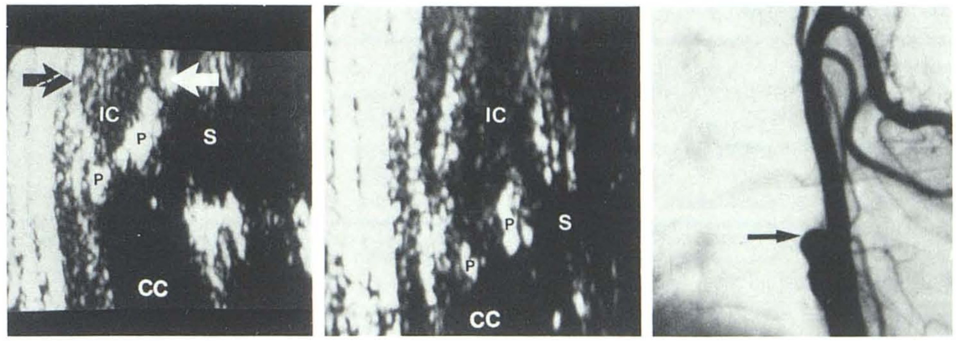


Fig. 6.—Complete occlusion of internal carotid artery. **A**, Echofree lumen of distal common carotid (CC) terminates in large echogenic focus (P) beyond which lumen is filled with material of lower echogenicity (*arrows*). Acoustic shadowing (S) deep to echogenic plaque. IC = internal carotid. **B**, Slightly higher level in neck. Numerous low-amplitude echoes in occluded proximal internal carotid. **C**, Angiogram. Total occlusion of internal carotid near its origin (*arrow*).

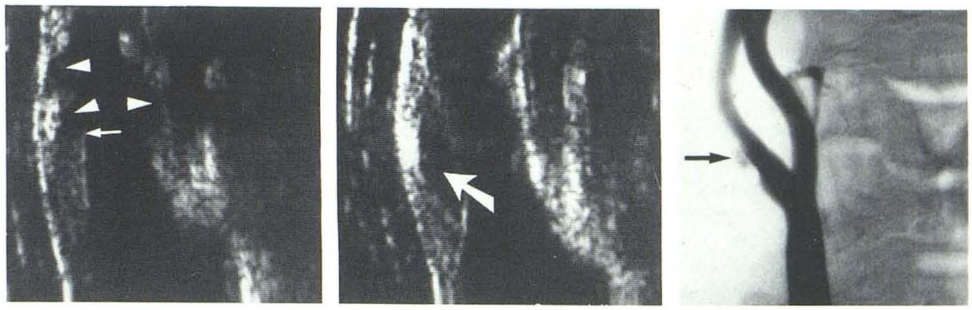


Fig. 7.—Ulcerated plaque. **A**, Long axis view of proximal internal carotid artery shows plaque with irregular surface (*arrowheads*). Abrupt discontinuity of surface intimal echo at proximal edge of irregular segment (*arrow*). **B**, Same lesion from more lateral scanning position. Large spindle-shaped anechoic area (*arrow*) within plaque on superficial wall of vessel. **C**, Angiogram. Large ulcer within plaque in proximal internal carotid (*arrow*).

more precise form in figure 8. The correlation coefficient r for these data is 0.875 ($p < 0.01$), indicating that, overall, there was close agreement between sonographic and angiographic estimates. The caliber of the internal carotid artery is, on average, about 5 mm, and we assumed that measurements of lumen diameter at angiography and sonography could be made no more accurately than ±1 mm [7]. Thus, values falling between ±20% of the line of identity in figure 2 were taken to represent acceptably close agreement. In 83 of the vessels, the difference in estimates of stenosis was acceptable and, in 14, unacceptable. Thirteen of the 14 vessels in the unacceptable group had flow-reducing lesions and included the seven cases of total occlusion not detected by sonography. To assess the source of error in these cases, the sonographic data were reviewed a second time together with the angiograms. In 12 of the 14 vessels, including the seven with complete occlusion, the error appeared to lie with the sonographic study. The boundaries between the vessel wall and its lumen were not sharply defined in the diseased area, resulting in inaccuracy of the estimate of stenosis. In the main, this was due to combined calcification and plaque of low echogenicity. In two vessels, no calcification was present, but the extent of low-echogenicity plaque had been substantially underestimated at the original interpretation. In the two vessels in which the angiographic estimate of stenosis appeared to be in error, the origins of the internal carotid arteries had not been well demonstrated on the angiograms. As a result, the stenoses had been difficult to measure accurately.

Discussion

While indirect noninvasive tests for carotid artery disease, such as periorbital directional Doppler sonography and oculoplethysmography, can detect stenoses or occlusions that decrease intracranial artery pressure, the location of the lesion cannot be identified. Most atheromatous plaques lie within 2 cm of the carotid bifurcation and can be well visualized by real-time sonography. Indirect tests remain necessary, however, because a cervical carotid lesion may be out of reach of an imaging system high up in the neck or in the carotid siphon [1].

The direct tests include continuous-wave [8] and pulsed Doppler sonographic imaging and audio systems [9–13], duplex instruments [14, 15], and B-mode high-resolution real-time sonography [2–6]. There has been widespread use of Doppler imaging systems and their modifications, and reports indicate an overall accuracy of 85%–96% in identifying major stenotic and occlusive lesions [16, 17]. Blackshear et al. [15], using a duplex scanner, reported a 92% accuracy in identifying high-grade stenosis or occlusion by audible analysis of Doppler signals. Reports of the use of high-resolution real-time sonography for carotid imaging indicate its value in demonstrating atheromatous plaque, but, with the exception of the report by Zweibel [6], there is little documentation of its value in assessing severity of disease in comparison with other methods. Acceptable correspondence of estimates of stenosis was obtained in 85% of vessels in our study and in 80% in the Zweibel series.

TABLE 1: **Assessment of the Degree of Arterial Narrowing by Angiography and Sonography**

Angiography	Total No. Carotid Vessels	Sonography				
		Normal	<50%	≥50%	Occlusion	Accuracy (%)
Normal	19	9	10	0	0	47
<50%	35	0	29	6	0	83
≥50	32	0	6	25	1	78
Occlusion	11	0	0	7	4	36

Note.—Accuracy in detection of flow-reducing lesions or occlusion = 86%; accuracy in detection of normal or non-flow-reducing lesions = 89%; and overall accuracy in distinguishing flow-reducing from non-flow-reducing lesions = 88%.

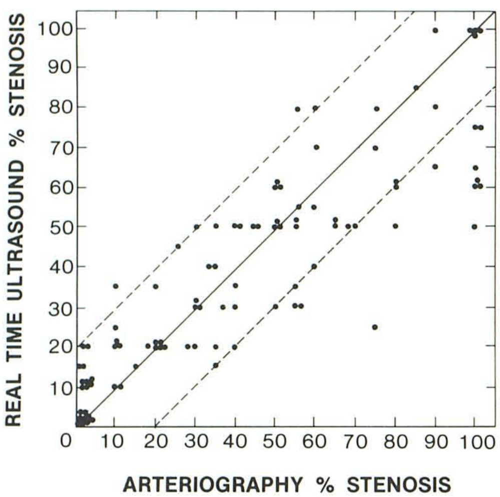


Fig. 8.—Real-time sonography versus angiography for internal carotid artery stenosis in 97 vessels from 50 patients.

Our accuracy in detection of flow-reducing lesions (≥50% or complete occlusion) was 86%. A similar accuracy was found by Zweibel, although a different criterion was used in defining a flow-reducing lesion. Our results also showed that accuracy of assessment of stenosis decreases with increasing severity of disease. Thirteen of 14 vessels, in which there was not acceptable agreement between estimates of stenosis, had lesions with ≥50% stenosis at angiography. Included in this group were all vessels with complete occlusion not detected by sonography.

The main factors contributing to error in these cases were calcification and material of low echogenicity within plaque. Both are often present in advanced atheroma and may contribute to poor demonstration of the residual lumen of the vessel at real-time imaging. In particular, it may prove impossible to distinguish between a high-grade stenosis and complete occlusion. A tight stenosis is usually an indication for surgery, whereas a chronic complete occlusion is inoperable. The distinction is thus crucial. Sonography failed to distinguish complete occlusion from a tight stenosis in seven patients in our study group. A high degree of accuracy, however, has been reported in the diagnosis of occlusion of the internal carotid artery by pulsed Doppler sonography [3, 11].

With experience, our ability in estimation of stenoses by imaging alone has improved. This is due to attention to several details of the scanning technique and image interpretation. The use of high instrument gain settings to amplify low-amplitude echoes has led to better demonstration of plaque of low echogenicity, or so-called "soft plaque." The presence of these lesions may be missed or their extent underestimated if gain settings are adjusted only to optimize high-amplitude signals in the image. Eccentric plaque may lead to error in estimation of stenosis if the vessel is imaged in only one plane. Scanning diseased areas in several longitudinal planes and in transverse section reduces this error [6]. Calcification in plaque may interfere with visualization of the lumen due to acoustic shadowing. It may involve only a portion of the vessel circumference, however, and scanning from different directions may allow the lumen to be viewed through a noncalcified area. Finally, if the common and internal carotid segment is severely diseased and no lumen can be identified, distinction between high-grade stenosis and occlusion may be made if patency of the distal internal carotid is shown. Patency is indicated by distensile pulsation of the vessel walls and lack of echoes within the lumen. It should be noted, however, that absence of pulsations of the distal internal carotid may be found with a tight stenosis as well as with occlusion. The distal internal carotid is often best shown by scanning high in the neck from a posterolateral approach. This is especially the case in subjects with a relatively high carotid bifurcation.

Problems associated with assessment of the severely diseased vessel may be largely overcome by simultaneous recording of hemodynamic data with range-gated pulsed Doppler. We recently had some experience with such a system incorporated into our real-time instrument. Flow characteristics within imaged vessels can be studied, and an audible, harsh, high-frequency signal is obtained when the volume sampler is placed within the lumen of a high-grade stenosis. Occlusion may be diagnosed by failure to detect flow within the lumen of the imaged vessel [14].

In several instances, we found small plaques at sonography when angiograms were normal. Image quality, in these circumstances, was good and the margins of the vessel lumen were well defined. It can be assumed, therefore, that false-positive diagnoses were not made in these cases and that the lesions were not appreciated at angiography. This is due to the small size of such plaques, the smooth surface of which blends with the adjacent normal vessel wall. They are better shown by sonography because the structure of the vessel wall is imaged and plaque is shown as a distinct band of tissue separate from the more echogenic media. Real-time scanning is also more sensitive in detecting non-flow-reducing lesions compared with methods using Doppler techniques. This is important because extensive plaque may be a source of emboli to the brain in the absence of significant reduction in flow. In the appropriate clinical context, such lesions may be considered an indication for further study leading perhaps to operative treatment.

Demonstration of plaque by real-time imaging provides a means of studying the epidemiology of atherosclerosis. The incidence, natural history, and response to therapy of the disease might be studied using this relatively simple noninvasive method. In addition, a clue to the histologic composition of plaques is provided by their echogenicity. In vitro studies have demonstrated that echogenicity is related to variation in the proportions of the principal tissue components of plaque, namely, lipid, fibrous tissue, and calcification [18]. Extension of these studies has led us to the conclusion that low echogenicity is related to a predominance of lipid in plaque; high echogenicity, with acoustic shadowing, to calcification; and intermediate echogenicity to a predominance of collagen.

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