Duplex sonography for carotid artery disease: an accurate technique.

D J Blasberg

AJNR Am J Neuroradiol 1982, 3 (6) 609-614
http://www.ajnr.org/content/3/6/609.citation

Duplex Sonography for Carotid Artery Disease:
An Accurate Technique

Dennis J. Blasberg[1]

Carotid arteriograms and combined real-time B-mode and Doppler sonograms were evaluated by independent observers of 101 carotid arteries in 51 consecutive patients. The results were correlated. For Duplex detection of hemodynamically significant stenosis, a specificity of 97% was obtained, sensitivity of 94%, and accuracy of 96%. The Duplex examination is an accurate method for evaluating carotid artery disease.

The results and accuracy of noninvasive evaluation of the carotid artery depend significantly on the technique and equipment used. We use a commercially available real-time 5 MHz sector scanner with Doppler frequency analyzer for examination of the carotid arteries. Initial experience with this unit for evaluating carotid artery disease in the common, internal, and external carotid arteries is reported.

Materials and Methods

Using an ATL Mark V Duplex sonographic unit (Advanced Technology Labs., Bellevue, WA), we evaluated the carotid arteries of about 250 patients in a 10 month interval. Of these patients, 51 had carotid arteriograms after the Duplex study. The time interval between the two studies was several hours to 99 days.

A single radiologist (D.B.) performed and interpreted all Duplex studies before arteriography. Duplex examination consisted of real-time B-mode scanning with a 5 MHz sector scanner that identifies the vascular anatomy and allows proper placement of the Doppler sample volume (fig. 1). We analyzed the pulsed Doppler signals with audio output and a zero-crossing discriminator. Using the criteria in table 1 developed before this study, the stenosis or occlusion was graded from analysis of Doppler audio output. A focal area of increased velocity (increased Doppler frequency shift) and increased turbulence (multiple Doppler frequency components or harshness) characterized a stenosis. We identified the internal and external carotid arteries by analyzing the M-mode output from the zero-crossing discriminator (fig. 2) and by analyzing the audio output. Anatomic location on B-mode scanning sometimes helped identify the internal and external carotid, but it was never the only method used.

Without prior knowledge of the Duplex findings, another radiologist (L. S.) evaluated the carotid arteriograms for area stenosis in either the common or internal carotid. Method of calculation is shown in figure 3. Data are presented in terms of area stenosis rather than diameter stenosis, because, for nonturbulent flow, the change in velocity of blood through a region of narrowing or stenosis is inversely proportional to the change in cross-sectional area.

We called a Duplex examination positive when it was either grade 3 or grade 3 or 4. On the basis of the empirical results of this study, the angiographic examination was considered positive when the area of stenosis exceeded 80% (see Discussion).

Results

We compared the Duplex findings with the measured angiographic stenosis in

Received August 7, 1981; accepted after revision June 8, 1982.

[1] Department of Radiology, Veterans Administration Hospital, Palo Alto, CA 94305. Present address: Desert Hospital, P.O. Box 1627, Palm Springs, CA 92263.

AJNR 3:609–614, November/December 1982
0195–6108/82/0306–0609 $00.00

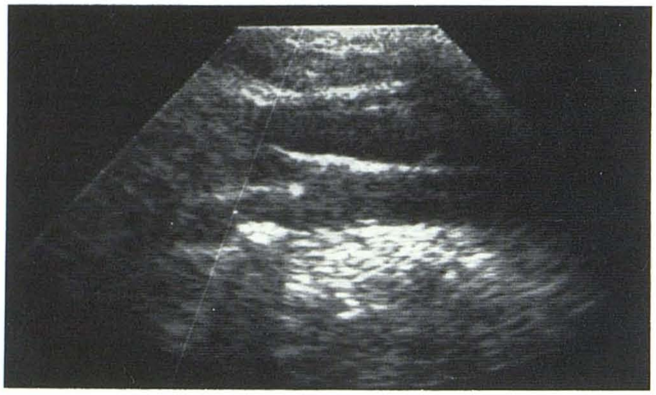

Fig. 1.—B-mode image of common and internal carotid arteries. Plaque in proximal internal carotid causes shadowing of sonographic beam. Dot (on cursor line) indicates location of Doppler sample volume.

TABLE 1: **Duplex Classification of Audio and M-Mode Characteristics of Carotid Artery Stenosis**

Lesion	Grade	Characteristics
Occluded	4	No flow identified (call as grade 3 or 4, as a preocclusive stenosis can be missed)
High grade	3	Marked harshness and very high-pitched focal velocity changes (very obvious)
Moderate	2	Harshness with definite focal increased velocity
Mild	1	Harshness with no significant focal velocity increase
Negative	0	Normal pitch and velocity with no broadening

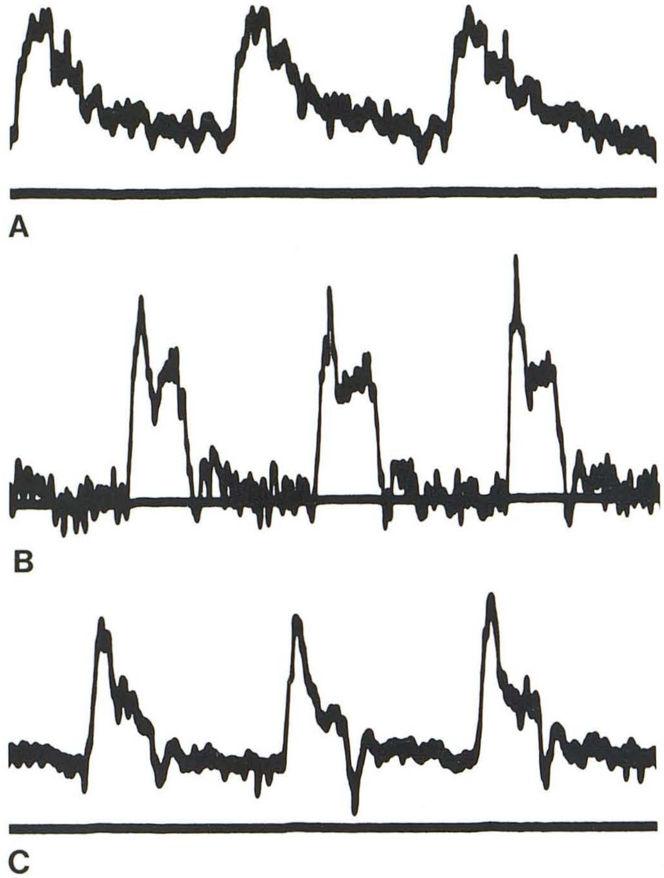

Fig. 2.—M-mode output from zero-crossing discriminator. **A**, Internal carotid. Gradual rise and fall of velocity through systole, usually no dicrotic notch, and considerable velocity remaining throughout diastole. **B**, External carotid. Rapid velocity rise in early systole, often two peaks in systole, rapid fall in velocity at end-systole with prominent dicrotic notch, and relatively small or absent velocity in diastole. **C**, Common carotid. Linear superposition of internal and external carotid velocity profiles.

figure 4. The Duplex study correlated well with the angiogram in 96 (95%) of 101 cases; it significantly overestimated the degree of stenosis in only one case. There was one case of a web, in which the angiographic area of stenosis could not be accurately estimated. An estimated area of stenosis of 93% was arbitrarily given to this lesion. The Duplex study of this vessel definitely underestimated the lesion, and this represents another "miss."

In the three other cases, the Duplex examination underestimated the angiographic stenosis for understandable reasons. In one case, the stenosis was so high in the cervical internal carotid (C1–C2 level) that we could not evaluate it. Although the two other cases had a focal stenosis in the proximal internal carotid, a much higher grade of stenosis existed in the carotid siphon; the siphon disease, not the bifurcation disease, limited blood flow and reduced or eliminated the expected turbulence in the proximal internal carotid stenosis. Therefore, we underestimated the degree of stenosis actually present.

We analyzed Doppler signals throughout the common and internal carotid arteries, and, for most cases, we evaluated at least 3 cm of the proximal internal carotid. Inadequate evaluation occurred in only one obese patient, where both carotid bifurcations were about 5 cm below the skin. In this patient, we correctly identified a high-grade stenosis of the right internal carotid artery, but could not satisfactorily evaluate for stenosis on the left.

Occasionally, B-mode scanning clearly shows a vessel representing the internal carotid, often with atheromatous plaque within it, but Doppler shows no flow within the vessel. Although this usually indicates total occlusion of the internal carotid, occasionally a very high-grade stenosis can be missed. Common carotid artery occlusion can be diagnosed reliably when no flow is seen within the vessel. In this study, Duplex examination could not identify flow in 11 internal carotid arteries. Arteriograms showed four very high-grade stenoses that were not detected on Duplex examination and seven occlusions. Duplex examination also showed no flow in one common carotid artery; aortic arch arteriography demonstrated occlusion of this vessel. Duplex study could not evaluate above the narrowest region in two cases of moderate gradually tapered stenosis of the internal carotid. We could not find a marked focal change in velocity; and

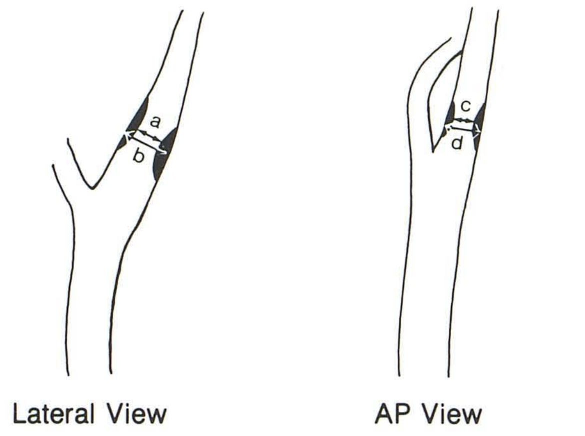

Fig. 3.—Calculation of percentage area of stenosis. *a* and *c* = diameter of narrowest region of lumen; *b* and *d* = estimated diameter of lumen at same level as *a* and *c*, assuming no atheromatous disease was present. Area of stenosis = $(1 - a/b \times c/d) \times 100\%$.

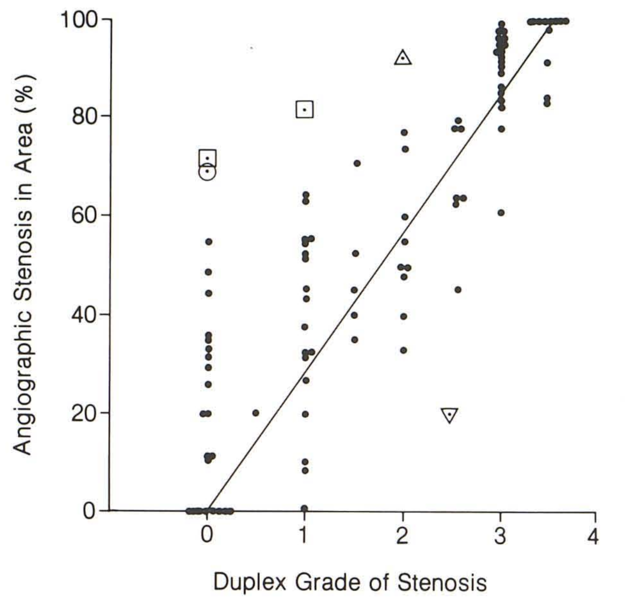

Fig. 4.—Duplex findings correlated with angiographic area of stenosis in 101 arteries. ⊙ = very high cervical lesion; ⊡ = significant carotid siphon disease; △ = web; ▽ = Duplex examination overestimated lesion.

since the internal carotid can normally taper more distally, we could not diagnose this type of lesion.

We expect variability both between different observers and the same observer at different times in interpreting degree of angiographic stenosis. Two different radiologists independently measured the angiographic stenosis, and the correlation is shown in figure 5. There was considerable variation in the lower-grade lesions, but very good correspondence in the high-grade lesions.

Of 101 arteries evaluated for hemodynamically significant stenosis by Duplex scanning, there were two false-positive, two false-negative, 32 true-positive, and 65 true-negative

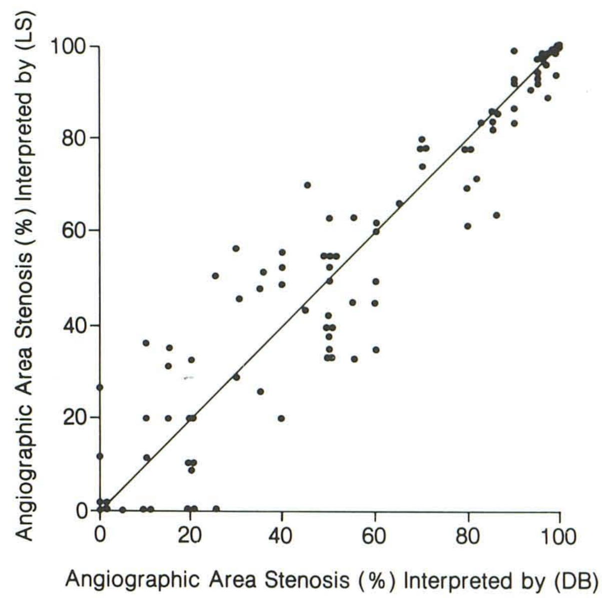

Fig. 5.—Calculation of area stenosis by two independent observers.

cases, yielding a specificity of 97%, sensitivity of 94%, and accuracy of 96%.

Discussion

At many medical centers, the carotid arteries are evaluated noninvasively with indirect tests such as periorbital directional Doppler sonography, oculoplethysmography, ophthalmodynamometry, and thermography, or with direct tests such as carotid phonoangiography. Newer methods of evaluating the carotid bifurcation are giving progressively better results as equipment and technique become more refined and as sonographers gain additional clinical experience. The results of these direct sonographic evaluations, however, depend on the equipment used. The design of commercially available sonographic equipment varies considerably, and includes continuous wave Doppler angiographic imaging [1, 2], B-mode scanning [3], and B-mode scanning combined with gated pulsed Doppler frequency analysis, also known as Duplex scanning. The commercially-available Duplex scanners also vary in design—some units emphasize the B-mode imaging capability while others emphasize the Doppler frequency analysis capability [4, 5]. This study evaluates a Duplex system that stresses Doppler frequency analysis.

At our institution, noninvasive evaluation of the carotid arteries was formerly performed using ophthalmodynamometry and carotid phonoangiography. Early results of the Duplex examination clearly showed its superiority for diagnosing both unilateral and bilateral disease; we recently stopped offering ophthalmodynamometry and carotid phonoangiography. The clinical services, particularly the neurosurgical and vascular surgical services, find the Duplex examination very accurate for their needs, and they find the examination often alters patient management (see below).

Developing skill in routinely evaluating the proximal 3 cm of the internal carotid artery requires substantial practice; both staff and residents learn Duplex scanning slowly and initially make many serious errors (fig. 6). We initially scan with a lateral approach using the sternocleidomastoid muscle as a window. The common carotid artery, which lies medial and posterior to the jugular vein, exhibits arterial pulsations with direction of flow cephalad. Carotid bifurcation usually widens on B-mode scanning and has associated decreased velocity profile on Doppler. Usually the internal, external, and common carotid arteries are not imaged at the same time unless they are in profile with the transducer; this rarely occurs, because most carotid bifurcations are orientated with the internal carotid posterior and lateral to the external carotid. However, we usually can easily image the combination of the common and internal or external carotid arteries.

The internal carotid usually lies lateral to the external carotid, although often it lies medial to the external carotid. The more distal part of the internal carotid usually curves posteriorly toward the mastoid, while the external carotid usually bends anteriorly toward the jaw. The jugular vein frequently crosses around the internal carotid just above its origin, and beginners often cannot follow the internal carotid by Doppler because they repeatedly enter the crossing jugular vein. When this occurs, they can usually find the more distal internal carotid by directing the angle of the transducer more posteriorly.

We reliably identify the internal or external carotid by examining the M-mode velocity profile from the zero-crossing discriminator (fig. 2). The brain is a low-resistance organ through which a large volume of blood flows during diastole. As systolic pressure slowly increases, blood flow in the internal carotid also slowly increases. Flow reaches a peak in midsystole and then decreases in the latter part of systole. Considerable (but gradually decreasing) flow continues during diastole. We usually do not see a dicrotic notch in the internal carotid velocity profile. If one is present, it will be small, particularly when compared with the external carotid dicrotic notch.

The systemic arterial system, of which the external carotid artery may be representative, has a high resistance that allows little or no blood flow during low pressures. The arterial pressure rises during early systole and a certain pressure is reached when the systemic arterioles open. This reduces the resistance and increases the flow in the external carotid distribution; hence, the external carotid velocity profile rapidly rises. A double peak of uncertain etiology often exists in midsystole. The external carotid velocity profile usually decreases rapidly at end-systole. Also, there is a prominent dicrotic notch in the external carotid velocity profile at end-systole, which, in some patients, results in momentary reversal of blood flow; this is related to the aortic valve closure. Flow during diastole can range from moderate to nil, but, in contrast to the internal carotid, relatively little diastolic flow exists compared with systolic flow. If the sonographer is uncertain as to whether a given vessel is the internal or external carotid, examining the velocity profile of the other vessel will usually resolve the issue. Indeed, the difference in physiology between brain and systemic system is much more reliable than locating the vessel anatomically. Learning the M-mode velocity profile of the internal and external carotid is rapid and easy. With some experience, audio identification of the vessels is possible. The internal carotid artery has a monotonous single varying sound; the external carotid, on the other hand, has a staccato type of complex sound that seems to consist of at least two separate components.

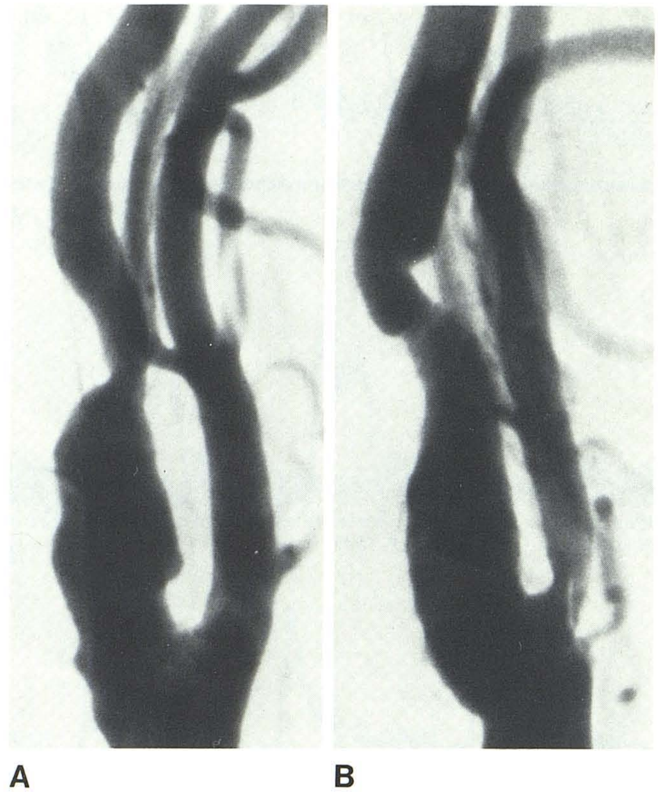

Fig. 6.—Carotid arteriograms. **A**, Right internal carotid with 64% area stenosis. **B**, Left internal carotid with 62% area stenosis. (AP view not shown.) Relatively inexperienced staff interpreted Duplex scan as negative bilaterally. They did not evaluate high enough. Repeat Duplex study before arteriography demonstrated high-grade stenosis on right and moderate- to high-grade stenosis on left.

Two groups have studied the superficial temporal artery before and after bypass surgery to the middle cerebral artery [6, 7]. Both have shown that before surgery the superior temporal artery had the expected external carotid type of velocity profile, but converted to an internal carotid type of velocity profile after a superficial temporal–middle cerebral artery anastamosis (since the superficial temporal supplies the low-resistance brain following the anastomosis). We have seen an occluded common carotid with retrograde flow in the ipsilateral external carotid resembling an external carotid velocity profile and a patent carotid bifurcation with antegrade flow in the ipsilateral internal carotid that resembled an internal carotid velocity profile.

The common carotid artery velocity profile is a linear superposition of the flow seen in the internal and external carotid arteries (fig. 2). The systolic part usually has a considerable structure, representing the external carotid contribution. The internal carotid generally contributes a large amount of the diastolic flow. If there is no diastolic flow in the common carotid, either high-grade stenosis or occlusion of the internal carotid could exist. However, accurate diagnosis requires complete Duplex evaluation of the internal carotid artery.

Stenoses

The Duplex grading of stenosis was established on empirical grounds by comparison with arteriography. We assume the velocity of blood flow is directly proportional to the mean Doppler-shifted frequency, and the turbulence at a stenosis is directly related to the increase in Doppler-shifted frequency components (which, on audio analysis, represents increased harshness of the sound). These terms will be used interchangeably. However, what is actually being interpreted is the audio and M-mode output of the Doppler frequency shifts, and not the actual velocity or turbulence.

In a focal stenosis of moderate grade (grade 2), Doppler sampling will show: (1) some turbulence just proximal to the stenosis; (2) focal area of easily identified velocity increase that drops off distal to the stenosis; (3) fairly harsh turbulence distal to the stenosis; and (4) characteristics of the velocity profile within the stenosis similar in appearance to the normal velocity profile proximal or distal to the stenosis.

The focal nature of the velocity increase and the turbulence allows a large degree of confidence in diagnosing the stenosis. We try to keep the angle of the sonographic beam to longitudinal axis of vessel lumen fixed (usually at about 60°) when scanning along the vessel, since the measured Doppler shift (measured velocity) is proportional to the cosine of this angle as well as the velocity of blood in the lumen. This can sometimes be difficult to achieve when the vessel is tortuous. Often, but not invariably, real-time imaging shows an atheromatous plaque in the region of the stenosis.

A mild degree of stenosis (grade 1) generally has a definite focal area of turbulence without a definite increase in velocity. A mild- to moderate-grade stenosis has focal turbulence with a questionable focal velocity increase.

A high-grade stenosis (grade 3) is characterized by a very high velocity (frequency) in both systole and diastole. The zero-crossing discriminator records very high velocity during diastole, and there may be reversal of the zero-crossing detector output during systole. This probably represents an artifact of the detector, as flow both proximal and distal to a high-grade stenosis is always cephalad. Velocity profile within the stenosis is dominated by the physiology of the stenosis, and not by the resistance distally. A high-grade stenosis of the internal or external carotid artery can, therefore, look identical, and identification of the other vessel becomes mandatory. Often, the velocity profile distal to the high-grade stenosis reverts back to that of the appropriate vessel, and this aids in identification. On the basis of this criterion for Duplex measurement of a high-grade stenosis (grade 3), the present study indicates empirically (see fig. 4) that such a stenosis corresponds to an angiographic area of stenosis of greater than 80%.

In a very tight or preocclusive stenosis, it is often difficult to locate the Doppler sample volume exactly at the stenosis, and positioning becomes very critical. Even with diligent scanning, we occasionally cannot detect flow in the stenotic region. In some of these cases, very slow flow is found in the distal nonstenotic part of the internal carotid artery. Occlusion should be suspected when no flow is detected within or distal to a region of atheromatous plaque, but we cannot exclude a very high-grade stenosis.

In evaluating for internal carotid stenosis, we take Doppler sampling throughout the length of the vessel, and evaluate as distally as possible. Generally, at least 3 cm of the proximal internal carotid should be evaluated as this includes most cervical internal carotid stenoses (fig. 6). Atheromatous plaque frequently causes shadowing of the sonographic beam, and limits pickup of Doppler signals. Transducer repositioning usually allows satisfactory Doppler signal pickup in these cases. We rarely see circumferential plaque causing complete sound attenuation; in these cases we can still detect turbulence and flow characteristics distal to the stenosis to evaluate its hemodynamic significance.

After surgery, increased turbulence is seen throughout the region of carotid endarterectomy, particularly near the proximal and distal aspects. Turbulence should not be given very much significance in these cases. Widening of the endarterectomized vessel is common, resulting in decreased velocity. Proximally and distally the vessel narrows to the normal luminal diameter, with an abrupt transition in velocity at these locations; this does not represent a stenosis. Focal stenosis can only be diagnosed if there is an abrupt increase in velocity through the stenosis that drops off again distal to the stenosis. Such a case of restenosis after endarterectomy was present in this study. An example of radiation fibrosis causing stenosis in the common carotid was also encountered in this study. In both cases, the patients were asymptomatic and no significant focal disease was suspected. Duplex examination prompted the angiographic study. The patient with restenosis subsequently had a repeat endarterectomy, and the patient with radiation fibrosis had a vein patch graft to his common carotid artery.

We analyze the Doppler-shifted frequencies with both audio output and zero-crossing discriminator output. A fast Fourier transform spectral analyzer was not available for this study; we believe it might be very helpful in quantifying turbulence, velocity, and changes in velocity, especially for milder grades of stenosis [8]. Doppler findings in high-grade stenoses are usually very obvious, and the excellent results of this study for hemodynamically significant stenoses probably will not appreciably improve when spectral analysis is used. We readily visualized atheromatous plaque on B-mode scanning with the ATL sonographic unit; indeed, probably 90% of the population group studied at our institution has visible atheromatous plaque. But this instrument cannot detect ulceration, and the degree of stenosis is determined by hemodyanmic changes rather than by the anatomy of the plaque and lumen.

ACKNOWLEDGMENTS

I thank Lynn Schmitz for calculating the arteriographic stenoses, Gerald Friedland for reviewing the manuscript, and Frances Mazzaferri for help in manuscript preparation.

REFERENCES

1. Bloch S, Baltaxe HA, Shoumaker RD. Reliability of Doppler scanning of the carotid bifurcation: angiographic correlation. *Radiology* **1979**;132:687–691
2. Weaver RG, Howard G, McKinney WM, Ball MR, Jones AM, Toole FG. Comparison of Doppler ultrasonography with arteriography of the carotid artery bifurcation. *Stroke* **1980**;11:402–404
3. Hobson RW, Berry SM, Katocs AS, O'Donnell JA, Jamil Z, Savitsky JP. Comparison of pulsed Doppler and real-time B-mode echo arteriography for noninvasive imaging of the extracranial carotid arteries. *Surgery* **1980**;87:286–392
4. Blackshear WM, Phillips DJ, Chikos PM, Harley JD, Thiele BL, Strandness DE. Carotid artery velocity patterns in normal and stenotic vessels. *Stroke* **1980**;11:67–71
5. Lusby RJ, Woodcock J, Skidmore R, Jeans W, Clifford PC, Baird RN. Carotid artery disease: a prospective evaluation of ultrasonic imaging in the detection of low and high grade stenosis. *Br J Surg* **1980**;67:823
6. Moritake K, Handa H, Yonekawa Y, Nagata I. Ultrasonic Doppler assessment of hemodynamics in superficial temporal artery–middle cerebral artery anastomosis. *Surg Neurol* **1980**;13:249–257
7. Tanaka K, Nukada T, Tsuda Y, Yoneda S, Imaizumi M, Iwata Y. Ultrasonic Doppler studies after superficial temporal–middle cerebral artery anastomosis. *Angiology* **1981**;32:128–136
8. Blackshear WM, Phillips DJ, Thiele BL, et al. Detection of carotid occlusive disease by ultrasonic imaging and pulsed Doppler spectrum analysis. *Surgery* **1979**;86:698–706

Book Review

1982 Year Book of Diagnostic Radiology. Edited by Walter M. Whitehouse, Douglass F. Adams, Joseph J. Bookstein, Trygve O. Gabrielsen, John F. Holt, William Martel, Terry M. Silver, and John R. Thornbury. Chicago: Year Book Medical, 492 pp., 1982. $41

Faced with a burgeoning volume of new information, the radiologist trying to keep up with the literature often resorts to scanning the cover pages of the radiology journals, and only on occasion dives in deeper to scrutinize articles of interest. The depth of knowledge acquired by this method is probably in inverse proportion to the quantity of information available, and, as the radiology journals increase in number, the problem of keeping up with the literature grows.

To a large degree, the format of pertinent literature review adopted by the section editors of the *Year Book of Diagnostic Radiology* overcomes the deficiencies in the scanning process described. With the 1982 issue, the year book celebrates its 50th year of continuous publication. The format is the same as in previous years: section editors reviewed the literature from about March 1980 to April 1981. If there is one criticism, it is the heavy concentration on United States radiology with only some 13% of the primary articles from foreign sources. Again, the editors' comments about the merits of the articles often are as valuable, or more so, than the primary reviews themselves, particularly since pithy editorial comments are liberally spread among the reviews. (I am certain many authors would welcome the opportunity for rebuttals!)

The able editorial comments were provided by the radiology faculty of the University of Michigan, who regrettably are making this their last edition. This group has achieved an excellent record in reviewing the progress of radiology in the United States over the past 11 years and deserves the thanks of all of us who need the literature to be condensed and placed in perspective.

With this volume, the group can be justifiably proud of a job well done. The yearbook stands as an excellent memento to their activities.

Samuel M. Wolpert
Tufts New England Medical Center
Boston, Massachusetts 02111