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Noninvasive Testing for Carotid Artery Stenosis:

I. Prospective Analysis of Three Methods

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Oculoplethysmography-carotid phonoangiography and periorbital directional Doppler sonography are two techniques widely used in the noninvasive evaluation of possible carotid artery disease. Recent advances with sonographic Doppler devices now permit measurement of blood velocities in the extracranial carotid arteries by direct scanning with a color coded Doppler imaging system. A prospective study involving 216 patients being evaluated for possible carotid insufficiency was carried out to compare the results obtained with these three methods. With stenosis 65% or greater at angiography, the accuracy of the Doppler imaging system was 94%, that of oculoplethysmography-carotid phonoangiography was 84%, and that of periorbital directional Doppler sonography was 80%. These results demonstrate that direct Doppler examination of the carotid bifurcation is superior to either of the other two techniques for the detection of carotid artery stenosis.

Over the past decade, numerous methods have been developed for noninvasively evaluating patients thought to be at risk for stroke. Several widely used techniques, including oculoplethysmography and periorbital directional Doppler sonography, indirectly evaluate carotid artery hemodynamics via the ophthalmic artery and its branches [1–5]. Others, including sonographic Doppler devices and high-resolution B-mode sonographic units, directly assess the hemodynamic and morphologic status of the extracranial carotid artery [6–13].

We report a prospective study of three noninvasive tests done to determine which most accurately evaluates the status of the carotid artery. Those studied were the White-Curry color coded continuous wave Doppler Echoflow scanner (DDI), periorbital directional Doppler sonography (PDDS) and combined oculoplethysmography-phonoangiography (OPG-CPA). All of these tests depend on alterations in blood flow as an indicator of abnormality and thus provide physiologic information that can identify significant hemodynamic stenoses.

Subjects and Methods

The color coded Doppler imaging device emits a 4 MHz continuous wave Doppler signal. The transducer head detects frequency shifts in the returning signal and identifies the peak velocity of the moving erythrocytes. In principle, the velocity of blood flow across a site of narrowing must increase if constant arterial flow is to be maintained [14]. The Doppler equation defines the relation between the increase in velocity of flow and the increase in frequency of the backscattered sonographic signals [15]. Peak frequency, or peak velocity, recorded by the transducer head is processed through a series of filters and displayed as a color coded dot on a monitor screen. An image is made up of a series of colored dots, each of which represents arterial velocity at peak cardiac systole. Peak velocities within the range of normal are displayed in red; those that are increased slightly over normal are displayed in yellow; and significantly

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A B

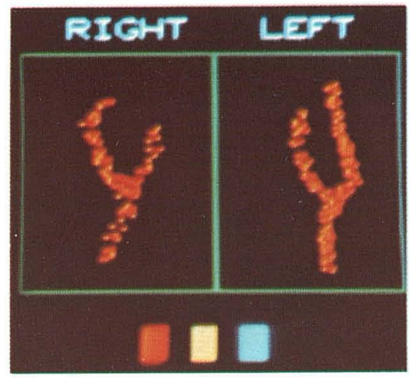

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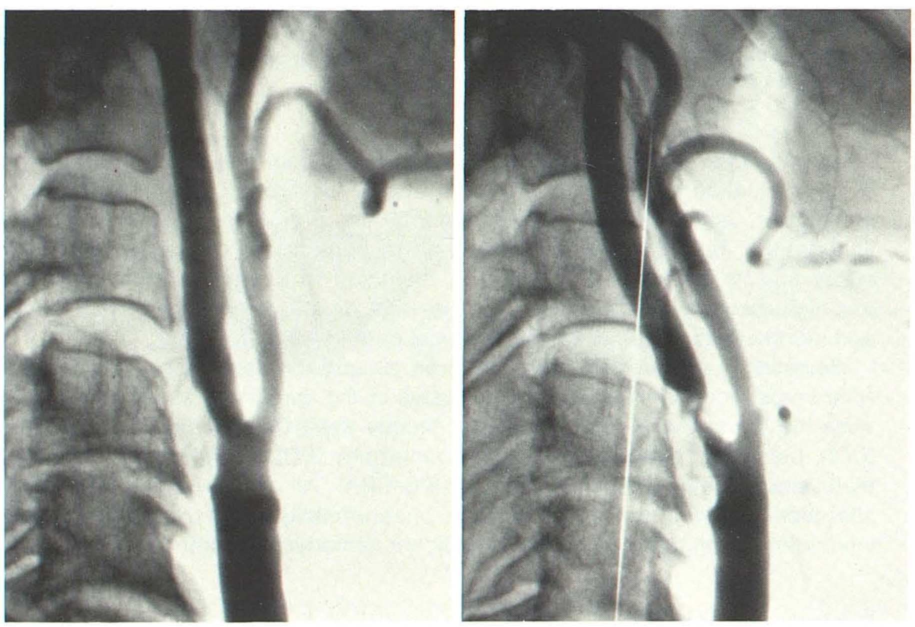
Fig. 1.—Contrast angiograms (**A** and **B**) and Doppler scan (**C**) of normal carotid arteries. Internal carotid artery is outer of paired vessels on color Doppler scan. Each red dot corresponds to moment of normal flow at peak cardiac systole.



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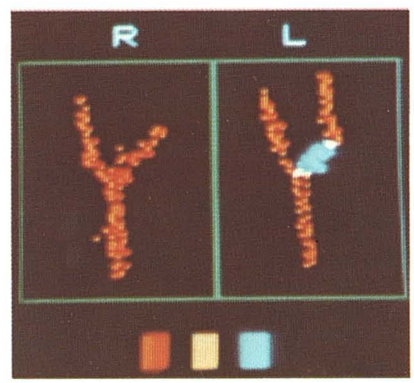

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Fig. 2.—Abnormal peak velocity (blue) at origin of left internal carotid artery on Doppler scan (**C**) corresponds to area of stenosis on contrast angiogram (**B**). Plaque at origin of right internal carotid artery on contrast angiogram (**A**) is not large enough to increase peak systolic velocity above normal limits on Doppler scan (**C**).

increased velocities are displayed in blue. The reflected signal is within the audible range and is broadcast, providing guidance in the construction and interpretation of the color image [16].

While the data is based on blood flow, the iamge obtained has an anatomic configuration displaying the common, internal, and external carotid arteries. A study was considered abnormal when segments of the common or internal carotid artery were coded blue, thus indicating areas of significant stenoses, or when the absence of a returning Doppler signal suggested total occlusion. Red and yellow dots identify peak systolic velocities that do not exceed the upper limits of normal, and such scans were interpreted as not suggestive of significant disease. A Polaroid picture of the color image provided a permanent record of each examination (figs. 1–4).

Periorbital directional Doppler sonography (PDDS) is an indirect test of carotid artery hemodynamics. The ophthalmic artery, the first major branch of the internal carotid artery, has anastomotic connections with branches of the

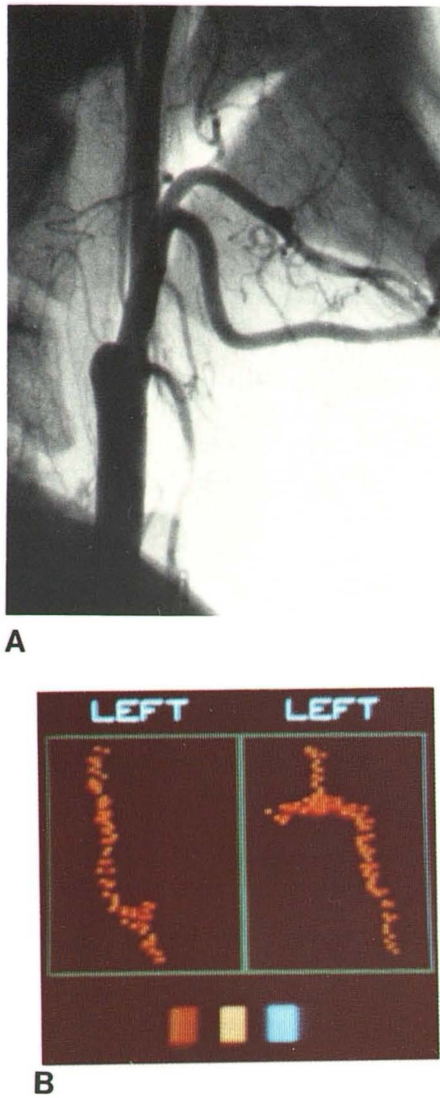

Fig. 3.—**A**, Contrast angiogram. Complete occlusion of left internal carotid artery. Patient subsequently had superficial temporal–middle cerebral artery anastomosis. **B**, Doppler image. Point of occlusion at bottom of box on left follows external carotid artery up to surgical burr hole at top of box on right. In this instance, the direct Doppler study obviated follow-up contrast angiogram after surgery.

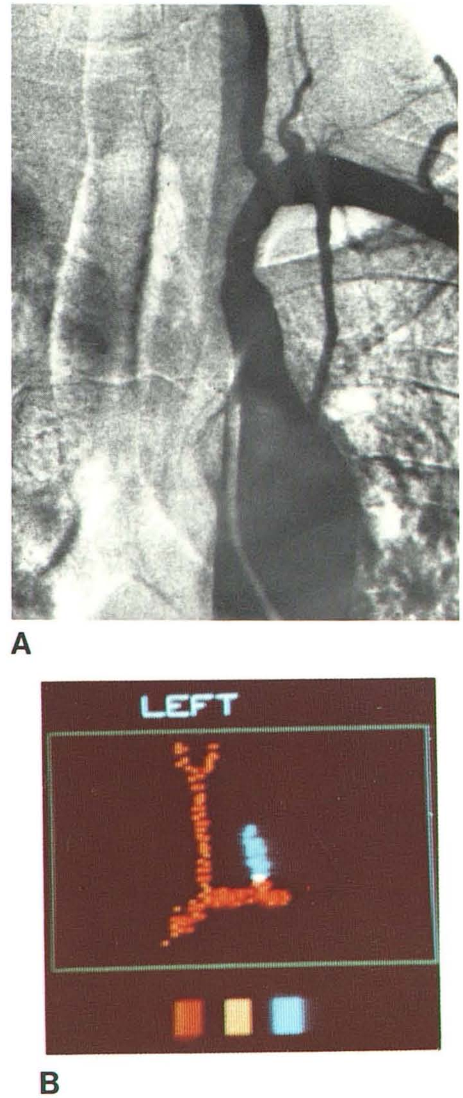

Fig. 4.—**A**, Contrast angiogram. Weblike defect at origin of left vertebral artery. **B**, Doppler tracing. Normal left carotid artery peak velocity (red) and abnormally increased flow (blue) in proximal left vertebral artery.

external carotid artery. Blood normally passes antegrade from the internal carotid artery through the ophthalmic artery to feed two terminal branches of that vessel, the supratrochlear and supraorbital arteries, which exit the orbit superiorly over the rim to supply the forehead. With stenosis of the internal carotid artery, this normal antegrade flow can reverse as the external carotid artery supplies collateral flow to the internal carotid territory via the ophthalmic artery and its branches [2, 17]. Using the Parks model 906 directional Doppler instrument, which uses a 10 MHz continuous wave signal, the direction of flow in the supratrocheal and supraorbital arteries was monitored first at rest and then after compression of certain branches of the external carotid artery. The test was considered positive if there was reversal of flow into the orbit in the resting stage or if there was a marked diminution or obliteration of flow with compression of the ipsilateral preauricular, facial, angular, or bridge arteries [3, 18].

Oculoplethysmography and carotid phonoangiography (OPG-CPA) were performed and interpreted as a single study according to the criteria of Kartchner et al. [1, 19]. The OPG part of the test is performed by applying saline-

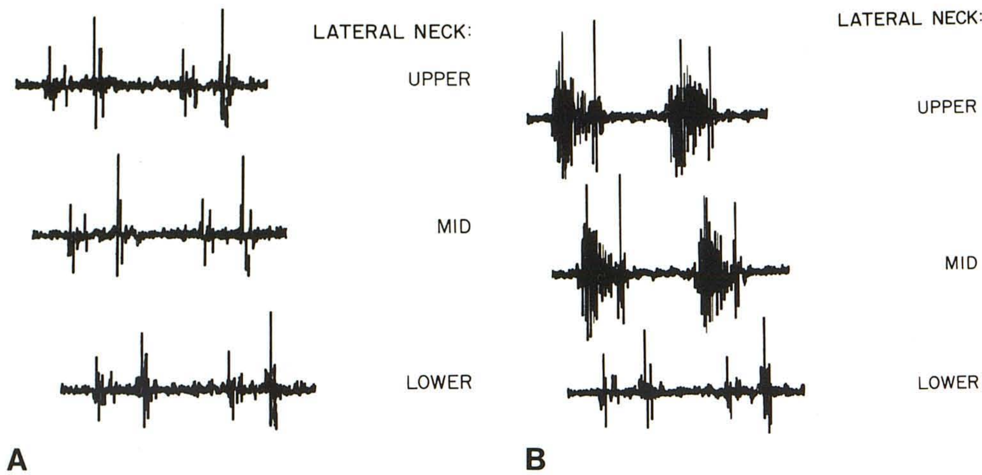

Fig. 5.—Carotid phonoangiography. **A**, Normal heart sounds and no bruit. **B**, Abnormal study. Significant bruit extends throughout systole and localizes to upper neck.

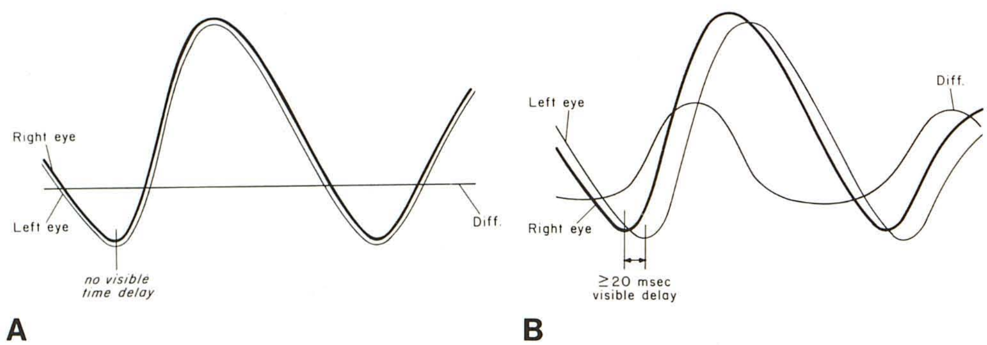

Fig. 6.—Oculoplethysmography. **A**, Normal. No delay in onset of upward deflection of either ocular pulse. Differential waveform is flat. **B**, Abnormal. Marked left ocular pulse delay, reflected in characteristic upward deflection of differential waveform.

filled cups directly to the cornea under 40–50 mm of suction to obtain ocular pulse wave forms generated secondary to the expansion of both globes during cardiac systole. These are recorded simultaneously on chart paper at 100 mm/sec, permitting comparison of the relative filling times. A differential wave form is electronically generated by subtracting the left ocular pulse from the right. A light opacity sensor is attached to each earlobe to measure the arrival time of the concomitant external carotid pulse.

Carotid phonoangiography (CPA) employs a hand-held microphone to obtain an oscilliscope recording of a detected bruit. Auscultation is carried out at three sites in the neck, high, middle, and low, along the anterior border of the sternocleidomastoid muscle. Bruit significance is assessed on the basis of its point of origin and its length in relation to the cardiac cycle. Since bruits may be transmitted to the carotid artery and not originate there, bruits that are recorded only in the low position or have their highest amplitude on the lowest tracings are discounted as arising proximal to the carotid arteries. Bruits that originate with the first heart sound and extend more than half way through systole are termed significant (fig. 5).

OPG tracings were considered positive for unilateral carotid disease if there was a visible delay (at least 20 msec) in the arrival of the ocular pulse from one eye compared with the other or if there was an abnormally delayed onset of the upward deflection of one ocular pulse (fig. 6) [1, 3, 19]. Bilateral disease was suggested when both ocular pulses were delayed relative to the ear pulse, when onset of the upward deflection of both ocular pulses was delayed, or when a significant bruit could be heard on the side opposite a recorded significant ocular delay. Bruits that extended through systole into diastole were considered to arise from the internal carotid artery and were interpreted as diagnostic of significant stenosis regardless of the OPG tracings.

All patients having no history of carotid surgery and scheduled for cerebral angiography for suspected cerebral vascular disease during an 18 month period were included in the study. A total of 216 individuals was examined, all of whom had DDI and PDDS. Because of eye pathology, uncooperative patients, and scheduling difficulties, only 176 of these also had OPG-CPA. Selective angiography was performed by catheterization of the common carotid artery using standard Seldinger technique. Magnification angiography of the carotid bifurcation was performed in at least two projections. The percentage of stenosis was determined by measuring the narrowest diameter seen on any view and dividing this by the diameter of the normal vessel distal to the stenosis. Narrowing of the residual lumen of the common or internal carotid artery by 65% or greater was considered significant.

The results from all three noninvasive tests were collected and compared with the angiographic results in order to evaluate efficacy of each test. The true-positive rate, a measure of sensitivity, is the proportion of positive tests in patients shown by angiography to have stenosis of 65% or greater. The true-negative rate, which describes the specificity of each test, is the proportion of negative tests in

TABLE 1: **Efficacy of DDI, PDDS, and OPG-CPA**

	DDI	PDDS	OPG-CPA
True-positive	103	67	77
True-negative	99	106	71
False-positive	10	3	13
False-negative	4	40	15
Accuracy	94% (202/216)	80% (173/216)	84% (148/176)
Sensitivity	96% (103/107)	63% (67/107)	84% (77/92)
Specificity	91% (99/109)	97% (106/109)	85% (71/84)

patients whose angiogram does not demonstrate significant disease [20]. A false-positive test has a positive noninvasive result for a patient whose subsequent angiography does not show significant disease, and a false-negative test is a normal noninvasive study for a patient with significant disease seen at angiography. The accuracy of each test is the total number of true-positive and true-negative results divided by the total number of tests performed.

Results

Angiography was positive for disease in 107 of the 216 patients. Among the 107 with positive results, 82 had surgery. In no case did the surgical findings reveal a degree of narrowing less than that shown by the angiogram.

The accuracy of DDI was 94%. In addition to being the most accurate of the three tests, it was the most sensitive, having a true-positive rate of 96% (table 1). Of the 10 false-positive studies, two were the result of kinking of the cervical carotid artery, one was the result of the false conclusion that there was complete occlusion of the internal carotid when in fact the vessel was completely normal, and the other seven occurred in patients with stenosis of 30%–60%. Three of the four false-negative studies occurred in patients with complete occlusion. In one patient the abnormality, obvious on repeat direct Doppler examination after angiography, was simply missed on the initial study.

PDDS had an accuracy of 80%, erring consistently in the direction of missing disease as reflected in the high number of false-negative studies. However, its specificity of 97% was the highest of the three tests. In all cases in which PDDS was correctly positive, subsequent angiography showed that the residual lumen of the carotid artery was narrowed by 75% or greater. Two of the false-positive studies were the result of occlusion of the ophthalmic artery, the OPG-CPA results also being positive in these cases.

The accuracy of OPG-CPA was 84%. Its sensitivity was 84% and its specificity 85%, OPG-CPA therefore proving neither as sensitive as DDI nor as specific as PDDS. CPA alone was not diagnostic in a single instance in this series.

If the criterion for a significant lesion was defined as a 50% reduction in diameter of the artery, the accuracy of DDI slipped to 91% (196/216), OPG-CPA to 80% (141/176), and PDDS to 75% (163/216).

Discussion

Each of these three noninvasive examinations has its strengths and weaknesses. Continuous wave direct Doppler scanning of the carotid artery requires very little patient cooperation, but does demand technical skill to perform. In almost all individuals the internal carotid artery lies posterior to the external carotid at their origin, and in about 90% of individuals, the internal also lies lateral to the external [21, 22]. By proper positioning of the transducer probe, the internal carotid artery can routinely be projected as the more lateral of the vessels displayed. When there is uncertainty, carefully following each vessel distally almost always distinguishes between the two arteries. The external carotid artery advances toward the junction of the mid and posterior thirds of the mandible, while the internal carotid artery moves more posteriorly behind the angle of the jaw. In addition, simultaneous compression of the ipsilateral superficial temporal and facial arteries can be performed manually while listening for a diminution in the audible signal from the external carotid artery. With careful scanning techniques, an experienced examiner should not confuse external carotid artery stenosis with common carotid or internal carotid artery disease.

Flow characteristics proved less helpful in distinguishing between the two major branches of the common carotid artery. A consistent change in the character of flow near the bifurcation is audibly apparent and alerts the examiner to the impending division of the common carotid artery. In normal individuals, the stronger, monophasic signal from the internal carotid artery can usually be distinguished from the biphasic, weaker signal from the external carotid. However, with disease and altered hemodynamic patterns, such a differentiation is severely hindered. The increase in pitch of the audio signal with increasing percentage of stenosis did prove helpful in approximating the size of the residual lumen of a diseased vessel. With very tight stenosis, in ranges exceeding 98% of the residual lumen, flow across the stenotic area may fall and the peak velocity will then decrease below the system's electronic threshold. The vessel will then appear occluded at a time when angiography demonstrates slow, delayed, antegrade flow. In two patients this same phenomenon was seen with very tight stenosis in the intracranial part of the internal carotid artery. With severe narrowing in one carotid, the opposite bifurcation may show increased peak velocity, suggesting significant disease on that side even when there is only a minimal lesion on the second side. This may reflect redistribution of blood to the contralateral carotid and caution is warranted in predicting bilateral disease on the basis of the DDI findings alone.

It is possible with DDI to image two branches of the external carotid and mistakenly conclude that one of them is the normal internal carotid when in fact there is a complete occlusion of this latter vessel. Three of the four false-negative DDI studies in this series occurred for this reason. Alternatively, an occlusion may be falsely diagnosed by not separating the external and internal carotid arteries when they lie close to each other. To avoid such errors, the probe should be advanced along each vessel, holding to a very tight sweep with the audio component utilized to insure that one does not move off the artery. By following each vessel distally as far as possible, one can be more confident as to which branch of the common carotid artery is pursued.

PDDS equipment is portable and the examination requires minimal patient cooperation. As has been reported by others, the test proved extremely reliable if clearly abnormal [3]. However, PDDS does require a high degree of operative skill to perform and interpret and proved to be quite insensitive, 63% in this series. There must be quite severe disease of the internal carotid artery before changes begin to occur in the normal antegrade flow in the supratrochlear and supraorbital arteries [3–5]. All our patients with abnormal PDDS tests proved to have stenosis of 75% or greater. There were many patients with quite a severe degree of stenosis who had normal PDDS tests as reflected by the high false-negative ratio. There were four patients in the series with complete occlusion of the internal carotid artery and normal PDDS studies.

The results obtained with OPG-CPA seemed in general accordance with those reported in other series [3, 5]. The test is easily performed and permanent tracings are obtained for later review by a skilled interpreter. OPG testing does require more patient cooperation than either of the other two examinations, and even alert indivduals without eye pathology do not always tolerate placement of the eye cups. Because OPG depends on comparing one side with the other, bilateral disease may yield a false-negative result. Significant disease of the ophthalmic artery can lead to a false-positive result with either OPG or PDDU. CPA proved helpful only as a supplement to the interpretation of the OPG data.

In summary, our data show that continuous wave Doppler imaging of the extracranial carotid artery is clearly superior to periorbital directional Doppler sonography and oculoplethysmography-carotid phonoangiography for the detection of carotid stenosis. None of the three techniques investigated can detect the presence of ulceration within plaque, and each test has certain inherent limitations that can lead to erroneous diagnoses. Therefore, even in combination, these studies do not eliminate the need for cerebral angiography in clearly symptomatic patients. Rather, their major role appears to be in screening and following individuals who might possibly be at risk for stroke, but whose clinical indications for invasive angiography are marginal.

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