Transorbital Doppler Diagnosis of Intracranial Arterial Stenosis

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SUMMARY Forty-two intracranial internal carotid arteries were visualized by both arteriography and 2 MHz pulse ultrasonic Doppler examinations. The intracranial internal carotid artery Doppler signals were studied at 5-7 cm depth behind the eyelid using frequency spectral analysis. Stenosis criteria were developed and methods of avoiding confusion with collateral effects devised. Among 33 intracranial ICAs visualized on the arteriograms, 22 were normal without stenosis and 11 displayed some degree of stenosis ranging from 20 to 75 percent. An additional 7 were totally occluded. Doppler criteria of stenosis representing elevated frequencies and symmetrical prominent low frequencies (SPLF) were utilized and separated from collateral effects to provide an overall accuracy of the technique of 88 percent with a 95 percent specificity and a 73 percent sensitivity. The technique appears sufficiently promising to justify further development and utilization.

NONINVASIVE ULTRASOUND techniques for detection of cerebrovascular disease in adults have been limited to the extracranial circulation because of problems with bone penetration. With development of improved instrumentation, using 2 MHz pulse wave Doppler (PWD) ultrasound, we can now detect blood flowing in all major arteries at the base of the brain. Three recently exploited pathways through the adult cranium are 1) transtemporal,1 2) transorbital,2 and 3) the transforamen magnum.3 This report describes the instrumentation and examination techniques for the transorbital pathway, the criteria and methods for diagnosing intracranial arterial stenosis and the assessment of intracranial collaterals.

Methods

Instrumentation

Two MHz pulsed Doppler ultrasound instrumentation was used with dual-crystal and single-crystal probes focussed at 5 cm (fig. 1). The diameter of the combined dual crystals was 12 mm and the single crystal 16 mm. The electronics* provides for a sample focal length of 5 mm. Two pulse repetition frequencies (PRF) 8.9 kHz and 6 kHz allows maximum velocity detections of 1.7 and 1 m/s respectively. The higher PRF is available for tissue depths from 2 to 8.5 cm and the lower PRF is used for 8.5-10 cm depths. A calibrated dial on the front panel of the instrument provides manual selection of focal depth. The ultrasonic power emitted at the probe surface was 50 mw/cm². High-pass "wall filter" settings are selectable at 300, 600, and 900 Hz to eliminate low frequency artery wall vibrations which obscure higher frequencies.

The two phase quadrature outputs of the Doppler detector were input to a fast Fourier transform (FFT) frequency spectral analyzer† operated at 2-second or 10-second sweeps on a dual polarity display. The polarity sense was arranged such that blood velocities moving away from the transducer were represented by frequencies on the positive scale while those moving towards the transducer were seen on the negative scale. The FFT generated spectrum provided the equivalent of 256 frequency bands updated every 10 milliseconds. Following the earlier experience with stenosis of the extracranial carotid arteries,4 we applied "wall filter" and "high boost" techniques. These techniques effectively attenuate low frequency energies less than 1 kHz and increase the representation of frequencies greater than 3 kHz. The upper cutoff frequency at 5 kHz was dictated by limitations of the ultrasonic pulse repetition rate.

Examination Technique

The patient examination was performed at the time of the regular extracranial CW Doppler referrals to the noninvasive vascular laboratory at the Providence Medical Center which includes Doppler imaging of the common carotid bifurcation, evaluation of orbital collaterals, and examination of the subclavian-vertebral artery systems. A pertinent physical examination included auscultation over both eyelids. The pulsed Doppler probe was placed sequentially over the left and right closed eyelids while directing the sound beam intracranially through the eye and the posterior orbit in either an anterior-posterior (AP) or oblique direction, figure 2. From the A-P direction (fig. 3) the superior orbital fissure and the optic canal provided pathways to both the parassellar and supraclinoid intracranial internal carotid artery (ICA) as well as the posterior communicating arteries when active. The oblique transorbital direction, figure 2, provided access through the roof of the orbit to the first segment of the contralateral anterior cerebral artery (ACA) at a depth of 6.5 cm.

From the AP direction signals from the cavernous sinus component of the ICA are found at a 5-7 cm depth at angles of less than 15° with the sagital plane slightly inferior to the horizontal plane. The supraclinoidal (distal) ICA signals were detected with a slightly superior angle. Thus, the entire course of the intracranial ICA was examined through the orbit. The pre-
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The referred technique is to find the ophthalmic artery signals at 4 cm and follow its direction to 5 through 6 cm. Slightly superior to the horizontal plane and with the focus at 6.5–7 cm the posterior communicating artery (PCoA) and the posterior cerebral artery (PCA) could also be found. These signals from blood flow in the posterior circulation were confirmed by their failure to be obliterated or were augmented by common carotid compression (CCC). If signals from the oblique direction arose from the cavernous ICA they were diminished or obliterated by homolateral CCC and augmented by contralateral CCC. If the signals from the oblique direction arose from the contralateral ACA they were diminished or reversed by contralateral CCC and augmented by homolateral CCC.

Stenosis Criteria

The Doppler spectral features of stenosis in the intracranial ICA were similar to those produced by stenosis in the cervical ICA and included 1) increased maximum frequency ($f_{max}$) exceeding the normal range and 2) prominent systolic low frequency energies with symmetrical representation above and below the baseline. These symmetrical prominent low-frequencies (SPLF) were graded from 0 to IV in strength. "I" represented the weakest seen and heard while "IV" designated the strongest spectrum seen and heard by experience. The SPLF signals were primarily confined to the systolic interval and did not extend into diastole unless they were of a musical quality. A musical “sea gull” or "moaning" quality Doppler spectrum was graded IV. Stenosis of the intracranial ICA was diagnosed when these criteria were found in the anterior moving A-P signals.

Collateral Effects

Collateral channels mimicked stenosis (e.g. when the ICA was occluded) producing high frequencies from the opposite ACA and SPLF developed at the ACoA. This ambiguity leading to a false diagnosis of stenosis was avoided by strict adherence to the A-P probe position and examination of the homolateral ACA from the opposite orbit to note any reversal of blood flow there.

Study Population

The experience in transorbital PWD reported here consisted of the first 300 patients studied during 1983 and 1984. "Normal" subjects were selected from among the patient population referred to the laboratory for dizziness only; who were without cardiorespiratory disease, demonstrated no bruits over the eyes, and no extracranial disease in the carotid or vertebral systems.

Twenty-three transorbital Doppler patients under-
went intracranial arteriography of adequate diagnostic quality. Patients were admitted to this study only if the arteriography was performed within six months of the transcranial Doppler examination yielding 42 satisfactory intracranial ICAs studied by both techniques. In all cases radiographic lateral views of the intracranial arteries were available and A-P views were also available in some. All Doppler examinations were made without knowledge of the arteriogram results, most of which were not made until after the noninvasive examination.

Results

Angiographic Findings

Among the 33 intracranial ICAs visualized on the arteriograms, 22 were normal without stenosis, and 11 displayed some degree of intracranial ICA stenosis, and an additional 7 were totally occluded. In one patient the cervical ICA was occluded while the intracranial ICA was filled via external artery collaterals. The degree of intracranial carotid stenosis varied from 30 to 75 percent and ranged in location from the petrous component in the carotid canal through the presellar and parasellar components to the genu of the ICA.

The contralateral artery was of interest in the patients with intracranial ICA stenosis. It was occluded in 5 of the 11 siphon stenosis patients and was 70–90 percent stenosed at its cervical origin in two others. The remaining 4 contralateral carotids were normal or less than 20 percent stenotic. In 7 of the 11 intracranial stenoses the homolateral cervical component had a normal diameter or was less than 20 percent stenosed. The remaining 4 cervical ICAs were severely diseased being 70–80 percent stenosed.

Clinical Correlates

Among the 11 siphon stenoses 6 were associated with an asymptomatic hemisphere. Stroke or lateralizing symptoms of TIA were present on the body side appropriate to the siphon stenosis in 4 patients seen, none of whom displayed greater than 20 percent stenosis in the homolateral cervical ICA. On the other hand all 4 patients with 70–80% stenosis in the cervical ICA were asymptomatic. Amaurosis fugax did not appear on the side of a siphon stenosis though it did occur with one occlusion and 2 normal siphons with 80–90 percent stenosis of the appropriate cervical ICA. Bruits were heard over the homolateral eye in 9 of the siphon stenoses and heard over two eyes when siphon stenosis was not present.

Doppler Findings

Systolic \( f_{\text{max}} \) obtained from intracranial ICAs in 15 normal patients, age 44–80 (65 years mean), averaged 1.4 kHz ranging ± 0.6 kHz. Assuming a 0 angle between the soundbeam and the ICA flow direction this represents a maximum systolic velocity of 56 cm/sec ± 24. Figure 4 illustrates the frequency spectrum obtained from the normal cavernous component of the ICA. The pulsatile characteristics are similar to those found in the cervical ICA; i.e., an elevated diastolic component as compared to branches of the external carotid artery. Frequencies from the normal contralateral ACA were similar.

In 8 of the ICS stenoses systolic SPLF signals of turbulence were found at 6–7 cm depth from the A-P direction. Six of the 11 stenoses produced a negative
systolic $f_{ma}$ exceeding 2 kHz. Figure 5A demonstrates both the high $f_{ma}$ and SPLF qualities associated with the stenosis in the cavernous ICA. In three cases of intracranial ICA stenosis normal frequencies were found at 6 cm depth and in one case $f_{ma}$ could not be displayed because the “high boost” technique was not yet implemented. In one of these three false negatives the turbulent signals of stenosis in the genu of the siphon were found but not recognized because the pulse depth at 5 cm was not recognized at the time as representing the intracranial signals of genu stenosis. No relationship could be established between the severity of stenosis and the Doppler signals.

In one case, without siphon stenosis, SPLF signs of turbulence associated with an elevated negative $f_{ma}$, were found at the 6 cm depth producing one false positive diagnosis of stenosis. In this case there was strong intracranial collateral to the opposite ACA due to 90 percent stenosis of the opposite carotid. The stenosis effect was probably detected at the ACoA due to inadvertent directing of the probe beam at the oblique angle. An orbital bruit was also present presumably from the same source.

Decision matrix analysis of this early experience in diagnosis of stenosis of the intracranial ICA disclosed an overall accuracy of 87 percent with specificity at 95 percent and sensitivity at 73 percent. The true negative index was 87 percent and the true positive index 89 percent. These results, from initial experience, indicate that the PW Doppler test for intracranial ICA stenosis performs best at indicating the presence of siphon stenosis and having more difficulty with false negatives produced by failure to find the stenosis signal. Accuracy may be increased with more experience, improved mapping techniques, and greater use of carotid compressions and high boost techniques.

Collateral Effects

The principal signal mimicking stenosis of the intracranial ICA is produced by high velocities in the collaterals flowing towards the transducer and producing turbulence at branch points. As the high velocities generated by the pressure gradient empty into a wider channel turbulences are produced, figure 6. Most of these collateral effects are caused by occlusion of the ICA and are usually eliminated from the diagnosis of stenosis by extracranial ultrasound examinations and by common carotid compression studies.

Orbital Bruits

The accuracy of an orbital bruit as a test for intracranial ICA stenosis was similar to our early Doppler
results but strong collateral effects and stenosis in the ACA appeared to produce bruits over the eye. Pulse Doppler, however, may be considered a highly focused microphone which can separate the source of turbulences which may or may not produce a bruit.

Discussion
Noninvasive diagnosis of intracranial vascular abnormalities is important because:
1) It adds to the general capability of noninvasive procedures for identification of lesions producing cerebrovascular symptoms and diminishes the need for invasive studies in some patients. Several centers in Europe and the USA are performing carotid endarterectomy on selected patients without angiography. One argument for holding to angiography in all patients considered for carotid endarterectomy is the possibility of a tandem lesion in the siphon. The techniques of this paper offer a noninvasive technique for detecting siphon stenosis. Many proponents of noninvasive diagnosis will be interested in this application.
2) When invasive contrast arteriography is necessary forewarning from Doppler examination of intracranial lesions help plan the arteriographic technique. In this day of DSA and sometimes limited views of intracranial vasculature, a lateral angiographic view may be important when siphon parasellar stenosis is found by Doppler. The finding by Doppler of a siphon parasellar stenosis may urge the radiologist to include lateral views during angiography.
3) When stenosis at the cervical origin of the ICA co-exists with intracranial stenosis it allows determination of the relative hemodynamic significance of the tandem lesions. Though currently we cannot determine the relative hemodynamic significance of tandem intracranial lesions, there is reason to believe improvements in transcranial Doppler techniques can achieve this end. Hemodynamic severity of carotid lesions can be judged by use of transtemporal recording of the MCA Doppler signal.
4) When other noninvasive studies of the common carotid bifurcation leave in doubt the questions of patency of the ICA, interrogation of the intracranial carotid artery can resolve the question and it can assist in monitoring patients during medical or surgical treatment. Progress or regression of siphon stenosis may someday be monitored by means of transcranial Doppler.

The transorbital approach is important because of the facility in reaching the internal carotid artery and the ACA both at an optimum Doppler ultrasound angle. The transorbital approach adds to the information already obtained from cervical Doppler and ultrasound imaging and enhances the intracranial information obtained from other transcranial pathways. This pathway provides more consistent access to the intracranial arteries than does the transtemporal pathway.

The Doppler spectral features of symmetrical low-frequency energies appears to be a representation of artery wall vibrations which replicate the sounds of the bruits heard with a stethoscope over a stenotic artery. This correspondence of the stethoscopic bruit and the Doppler representation of the bruit is especially striking when a "sea gull" or "harmonic" quality is heard by both techniques. The Doppler representation of these harmonic bruits reproduce the pitch heard with the stethoscope. Hoeks has provided the explanation for this observation. Regardless of the ultrasonic carrier frequency when the excursions of the artery walls are considerably less than that of one wave length of ultrasound, the frequencies of the vessel wall excursions are reproduced in the frequencies of the Doppler signal and the frequency content of the Doppler signal is matching the frequency content of the stethoscopic bruit. Bruits heard with the stethoscope over the eyelid appeared to be a promising test for diagnosis of stenosis of the intracranial ICS but the nondirectionality of the stethoscope limits its accuracy.

The 40 mW/cm2 of 2 MHz pulsed ultrasound measured at the transducer surface and calculated to be 18 mW/cm2 at the 3 cm depth of the retina is believed to be safe for the eye because:
1. 50 mW/cm2 continuous wave ultrasound focussed at 3 cm has been used in our laboratories for 14 years over the eyes of at least 20,000 patients without complaint or known adverse effects.
2. The retina does not respond with visual effects. Patients and normal technician volunteers, including the authors, routinely deny any sensation of heat or light when questioned.
3. Cataract has been shown in experimental animals only with power at 230 W/cm2.
4. Heating of the transducer is not sensed by the eyelid and would probably accompany power sufficient to damage the cornea.
5. 18 mW/cm2 "in situ" is comparable to 17 mW/cm2 reported for ophthalmic scanners in their publication 510(K) Guide.

The results of this study should be considered preliminary because the instrumentation and examination techniques were evolving. The current methods were not completely used on all patients. More patients with high resolution angiograms must be examined to establish the true diagnostic accuracy of transcranial Doppler. When intracranial ultrasound imaging techniques1-7 are developed the full potential and accuracy of transcranial Doppler diagnosis will be apparent.

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References
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Duplex Scanning of Normal Vertebral Arteries

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SUMMARY Vertebral arteries were studied by Duplex scanning in 50 normal subjects. Pretransverse and C6-C5, C5-C4 intertransverse segments were visualized in all cases on both sides; segment C4-C3 was visualized in 100% of the cases on the right side and in 90% on the left; ostium was obtained in 94% of the cases on the right and in 60% on the left. The left vertebral artery was dominant in 48% of the cases while the right vertebral artery was dominant in 14%. Three vertebral arteries were hypoplasic. Duplex scanning was thus found to be an easily performed noninvasive method to study morphological and hemodynamic characteristics of vertebral arteries from their origin to the C4-C3 level.

Equipment

The study was performed with duplex scanning equipment (Biosound) which includes, in the first place, a system for imaging arterial walls and their content (B. mode echo), and secondly, a pulsed Doppler with a sample volume of 1 mm3 for analysis of flow velocity wherever blood vessels are visualized.

This high resolution ultrasound duplex scanner utilized a transducer with an average frequency of 8 Megahertz.

The echographic image, obtained when the probe is placed over the artery, is viewed on a screen in real time, at a frequency of 50 images per second. Its size is 3 cm by 4. Axial resolution, improved by dynamic focusing of reflected ultrasounds, is approximately 0.3 mm. Recordings were obtained by direct polaroid photography of the screen and by video recording of selected sequences.

Examination Procedure

The examination procedure was identical for all subjects. The patients were all in supine position, head slightly turned away from the explored artery and shoulders kept down. Maximum forced expiration was requested of each patient.

The probe was first placed in the supra-clavicular notch and adjusted laterally to detect the bifurcation of the subclavian trunk, the subclavian artery, and the origin of the vertebral artery. The pre-transverse segment of the vertebral artery was followed up to its entry into the transverse canal. The probe was then directed...
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