DOPPLER-SHIFT ultrasound has been used as a non-invasive test to diagnose disease of the carotid arteries for some years. More recently, the diagnostic accuracy of the method has been improved by using spectral analysis. In 1972 a transducer was connected to a position-sensing arm by Spencer and Reid so that an ultrasonic image of the carotid bifurcation could be obtained. Visualization of the arteries in this area is important because if disease is present it can be treated surgically.

This is a preliminary report on our experience using continuous-wave ultrasound and a directional Doppler velocimeter to image the extracranial carotid arteries. The image should be termed a physiological one, as the method depends on detecting blood flow-velocities beneath a transducer which is guided over the surface of the neck. The advantages of this method over arteriography, which produces a morphological picture, are that there is no attendant risk and the examination can be repeated at intervals as frequently as required.

The imaging system developed in our laboratory is used in conjunction with a spectral analyzer which displays the Doppler-shift audio signals simultaneously with the build-up of the image. This display confirms which of the carotid arteries is being scanned and clearly indicates changes in relative velocity as the various image points are formed. A further important aspect of the instrumentation is that registration of the image is principally dependent on the power, as opposed to the frequency, of back-scattered signals. Thus, since the power in the Doppler signals from the carotid vessels is almost constant throughout the cardiac cycle, the image can be built up continuously.

This allows an image of the vessels around the bifurcation to be built up within 10 minutes.

Instrumentation

The Continuous-Wave (CW) Imaging System (fig. 1) was designed in our laboratory and has been described elsewhere. It consists principally of 1) Transducer and Directional Doppler-shift velocimeter, 2) Scanning Arm Assembly, 3) Spectral Analyser (Spectrascribe), 4) Microprocessor, image store and keyboard.

The transducer consists of 2 identical piezoelectric crystals, one of which transmits continuous wave (CW) ultrasound at a frequency of 5 Megahertz, and the other receives back-scattered signals from moving blood corpuscles. The 2 crystals are broadly focused at between 2-4 cm from their faces, which is the approximate depth of the carotid arteries beneath the skin. The transducer is linked to a mechanical scanning arm and a directional Doppler-shift velocimeter. The velocimeter generates distinct and, if necessary, simultaneous forward and reverse flow-velocity channels by the use of a phase quadrature detection system. This equipment is fastened to a support above the patient's head and is connected to a spectral analyzer (Spectrascribe), a CW image processor and a dual oscilloscope display unit. One oscilloscope displays the vessel image, while the other displays the Doppler-shift signals in sonagram form (fig. 2). These sonagrams are written continuously across the screen, and refreshed every 3 seconds. A sonagram shows Doppler-shift frequency on the Y axis and time on the X axis. The blackness of the trace at any point is related to the number of blood corpuscles travelling at that velocity within the ultrasound beam. By inspecting the sonagrams and simultaneously hearing the signals with a pair of headphones, the operator can be certain which carotid artery is being imaged. This

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FIGURE 1. Continuous-Wave Ultrasound Imaging System.

Combination of a spectral analysis display of the blood velocities coincident with the build-up of an image and digital processing of the analyzer output prior to image formation are two of the features which distinguish this system from other imaging systems being developed elsewhere. The position of the transducer on the neck is translated to the X and Y axes on the storage oscilloscope by two potentiometers fixed to the scanning arm. Movements of the arm in the horizontal (head to foot) and vertical directions relate to the X and Y axes on the image oscilloscope respectively. Movements of the arm at right angles to the XY plane, that is, in the Z direction, are not registered on the oscilloscope and allow for the contours of the neck. Any non-linear position sensing arrangement can be used because the microprocessor can correct to linear XY coordinates. Thus a lightweight compact scanning arm can be employed and scan data can be re-centered for a second scan at any time by a microprocessor command via the system keyboard. Patient details can be entered and edited via this keyboard and stored for display together with the final image (figs. 1 and 2).

A beam of CW ultrasound passes from the transducing crystal into the neck along the Z direction, and when blood flow is sensed, a bright spot is permanently registered on the image screen. The total of such “frozen” images as the transducer scans the width and length of an artery completes a physiological “flow” picture of the lumen. This is in contradistinction to the arteriogram which presents a morphological picture of the vessels. The microprocessor scans the instantaneous blood-velocity spectrum as it is formed. Therefore, detection formats for image bright-up other than Doppler frequency threshold can be programmed into the system. In the present arrangement a low threshold is set in both power and frequency, just sufficient to ensure that low frequency signals due to arterial wall movement are rejected and that spurious signals due to noise or transducer movement artifacts are not incorporated into the image. Therefore, since the power of Doppler-shifted signals, as distinct from their frequency, is virtually constant throughout the cardiac cycle the image can be formed equally well in diastole as in systole, considerably lessening the time required to produce an image. The system is also directional, separating forward from reverse flow, so that venous flow is not registered on the image when the carotid arteries are being visualized.

Method

The patient lies on a couch and the importance of keeping the head still during examination is explained.
In most cases it is not necessary to use any means to restrict head movement, but lateral pads may be used if required. A generous quantity of ultrasound coupling gel is placed on the area to be scanned and then the positions of the external carotid (EC) and internal carotid (IC) arteries are found by listening to the Doppler-shift signals from these vessels and simultaneously inspecting their sonagrams on the display oscilloscope. A lateral view is obtained by setting the transducer as near to right angles as possible to the scanning arm. In order to obtain a reasonable Doppler-shift in frequency the transducer is also set pointing toward the head at a constant angle of approximately 60 degrees to the plane of the neck. When the transducer is fixed in position no rotational movement is possible. A more sensitive control of the scanning arm is obtained if both hands are used to direct it, one hand holding the transducer and the other holding the scanning arm a few inches higher. The position of the transducer on the neck is shown on the image screen by a flashing spot. This demonstrates to the operator the precise position of the transducer relative to the image already formed on the screen.

It is helpful to perform a rapid scan, taking only 1-2 minutes, in the first instance. This gives further information to the examiner on the relative positions of the common carotid (CC), EC and IC arteries, so that when the detailed scan is undertaken less "searching" for these vessels is necessary. This is important because best results are obtained when only a single pass is made over each part of the vessel. Returning to areas already scanned can cause errors due to slight head movement. After this initial scan the screen is cleared and a detailed scan performed starting as low as possible in the neck over the CC artery. The scanning arm is moved vertically, thereby crossing the artery in an antero-posterior (A-P) direction (fig. 3). Each vertical movement is continued until no further signal is heard in the earphones or seen on the spectral analyzer display so that the examiner is certain that the transducer has crossed the total vessel lumen. As the transducer is placed lightly on the skin no distortion of the underlying vessels occurs. Having passed up the CC artery a clear separation of the IC and EC arteries near their origin can usually be established, and then each of these arteries is visualized separately, thus completing a lateral view. An A-P view of the junction may then be taken by turning the patient on his side so that the side of the neck to be scanned is uppermost. The head is supported by a firm pillow and a further scan performed as described above. Performing each scan in this way takes between 10-15 minutes, and, therefore, if 2 views are necessary the examination takes approximately 30 minutes. The process can be repeated on the opposite side of the neck if required, and a picture of each image is taken with a Polaroid camera.

Results

An example of the ultrasound image obtained with a lateral view of the carotid bifurcation in a healthy young volunteer is shown in figure 4 (a). The IC can usually be imaged for a greater length of its course than the EC artery. Further, since the IC is usually

Figure 3. Transducer and scanning arm configuration to obtain a lateral projection of the carotid junction, i.e. a "lateral scan."

Figure 4. Ultrasound images of the carotid bifurcation in a healthy young volunteer, a) Lateral scan showing that in this view the internal is inferior to external carotid artery. b) A/P view in which the internal is superior to external carotid.
FIGURE 5. Ultrasound image of internal jugular vein in a healthy young volunteer.

posterior to the EC artery near the junction a lateral view from either side of the neck shows the IC inferior to the EC artery. Figure 4 (b) demonstrates the A/P view of the carotid bifurcation shown in Figure 4 (a). In this position the IC is superior to the EC artery as the IC lies lateral to the EC artery near the junction.

It should be emphasized that the use of a spectral analysis display as the image is being made is essential for confirming which artery is being scanned. This is especially important when either the angle of the transducer or the patient’s position is altered. Furthermore, when disease is present, which may cause distorted Doppler-shift signals, visualization of the waveform shapes by spectral analysis may be the only way of knowing which artery is being scanned.

The directional properties of the system enable it to visualize at command either forward or reverse flow. Figure 5 illustrates the use of reverse mode imaging and shows the internal jugular vein in a healthy volunteer.

Disease of the carotid arteries is shown by 1) interruptions in the continuity of the ultrasound image outline and 2) distorted or turbulent Doppler-shift signals seen on the spectral analysis display, which occur simultaneously with the interruptions demonstrated on the image. These changes are illustrated by the cases presented below, in which the ultrasound images are compared with carotid arteriograms.

a) Disease of Internal Carotid Artery

An ultrasound image and carotid arteriogram (lateral views) from a 67-year-old man with transient ischemic attacks are compared in figure 6. It should be noted that neither the angle of the projection, nor the magnification are the same in the 2 images. An example of a bilateral block of the IC artery in a 45-year-old man is shown in figure 7. It may be seen that in both cases a considerable length of the EC artery has been visualized. In the cases we have examined it would appear that, in agreement with the report by Spencer et al., if severe disease is confined to either the IC or EC artery then the artery without disease can usually be imaged for a greater length of its course.

b) Disease of External Carotid Artery

Figures 8 and 9 compare the lateral and A/P views of both x-ray and ultrasound images of the right carotid bifurcation in a 49-year-old woman. She had a bruit in the neck associated with amaurosis fugax affecting the right eye. Neither the ultrasound nor
x-ray lateral views demonstrated any definite lesions. However, abnormal velocity waveforms were observed during the formation of the EC ultrasound image. An A/P ultrasound view clearly shows a lesion in the EC artery, which is confirmed by the arteriogram. This illustrates the importance of scanning in more than one plane.

c) Generalized Disease

The ultrasound image and carotid arteriogram shown in figure 10 are from a 65-year-old man presenting with transient ischemic attacks and having a bruit in the neck. The Doppler-shift signals from all 3 arteries were turbulent throughout their course in the neck. The effect of this turbulence on the sonagram from the IC artery is shown in figure 11.

d) Disease of Common Carotid Artery

An ultrasound image from a patient who had an endarterectomy performed some years previously for a severe lesion in the IC artery is shown in figure 12. The patient later developed further symptoms and subsequently an arch aortogram demonstrated that the CC artery was blocked. The carotid junction was therefore not visualized on the x-ray. The directional Doppler velocimeter showed that blood was flowing down the IC and then up the EC artery. During the scan the IC was visualized down to the bifurcation and then the short length of CC that was patent was also visualized. When no further signals from the CC were detected the sensing mechanism was reset to visualize flow in the reverse direction only, and an image of the EC artery was then obtained.

Discussion

We have been encouraged by the initial results using this non-invasive method for visualizing the carotid bifurcation, especially as a satisfactory image can be produced quickly. There is good agreement between the CW ultrasound image and carotid arteriograms as has been reported by Spencer et al.\textsuperscript{11} for a different CW system.
A more sophisticated method of imaging using pulsed Doppler-shift ultrasound has been described by Mozersky and by Fish. In addition to displaying longitudinal views this system can image blood flow velocities at any required depth, and, therefore, a cross-sectional view of the lumen can be built up and held in computer store. Although this system has obvious scientific advantages we felt justified in exploring the use of a CW system because it is cheaper and in some respects easier to use. As inaccurate results are obtained in both systems if slight head movements occur during the examination, the speed with which a scan can be performed is, in our view, most important. Although we believe that a pulsed Doppler system is capable of producing more information, this additional data may not, at the present time, alter patient management. During carotid arteriography lateral and A-P views of the carotid bifurcation are obtained. In some cases oblique views are also taken. As these views can be obtained using a CW ultrasound system we feel that this method of imaging may be sufficient for effective patient management. However, a pulsed Doppler system can quantify the size of a lesion with greater accuracy, and, therefore, can give additional information about the progression or regression of atheroma in controlled research conditions, e.g., monitoring the effectiveness of any proposed drug stimulating regression of atheroma.

Some disadvantages of both the CW and pulsed Doppler systems are:

a) Resolution of both systems is unlikely to be sufficient to convincingly demonstrate the presence of small lesions, e.g., 'minimal' atheroma, plaques intruding into the lumen by <1 mm.

b) They rely on the patient's head remaining still during the examination.

c) They are unable to give any information about the intracranial vessels because of the high acoustic impedance of bone.

d) As the ultrasound used in these investigations does not penetrate calcium neither system can differentiate between the presence of calcium associated with atheroma, and the presence of calcium in the arterial wall without atheromatous deposits. In both of these situations the ultrasound image would suggest...
the presence of atheroma by demonstrating interruptions in the image outline.

For these reasons we are using imaging in conjunction with a primary examination by our other non-invasive method for assessment of the carotid vessels. This method involves analysis of Doppler-shift sonograms obtained from the supraorbital and carotid arteries as described elsewhere. When disease of the carotid artery is suggested by this primary examination, and the ultrasound image fails to demonstrate disease in the A-P and lateral views, care is taken to scan at different angles. Failure to demonstrate an abnormality with these different views suggests that the lesion is either small or lies in the intracranial portion of the IC artery. We have found that this primary examination helps to differentiate between the presence of calcium with or without atheromatous involvement, since the sonograms obtained during this examination are within normal limits when there is no atheroma present.

We now believe that a CW Doppler-shift imaging system can be used with good effect in the initial assessment of patients with a bruit in the neck, and those presenting with symptoms suggestive of transient ischemic attacks. This system can help to differentiate between a partially stenosed and occluded IC artery. This is important for if the IC is occluded endarterectomy is not usually undertaken and, therefore, an arteriogram is unnecessary. It may also be used to assess the carotid vessels in patients presenting with symptoms due to vascular disease at sites other than the head and neck. Elderly patients undergoing any operation which requires a general anesthetic would benefit from having preoperative assessment of their carotid arteries by this non-invasive method.

Acknowledgments

We are most grateful to the Medical Research Council for the financial support which has made this work possible. We would like to thank Dr. J. M. Reid of the Institute of Environmental Medicine and Physiology, Seattle, Washington, USA, for supplying the transducer and some of the electronics for the directional Doppler-shift velocimeter. Our thanks are also extended to physicians and surgeons at Guy’s Hospital who allowed access to patients under their care, and to personnel in the x-ray Department for their assistance. Finally, we gratefully acknowledge all the advice and constructive assistance from fellow members of the Guy’s Non-Invasive Angiology Research Group and members of the photographic department.

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Imaging the carotid bifurcation using continuous-wave Doppler-shift ultrasound and spectral analysis.
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Stroke. 1978;9:465-471
doi: 10.1161/01.STR.9.5.465

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