REVIEW ARTICLES

Clinical diagnosis by transcutaneous Doppler ultrasound

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Summary

Transcutaneous Doppler ultrasound represents a convenient, reliable technique for the non-invasive diagnosis and assessment of a rapidly increasing number of diverse circulatory disorders.

Introduction

The past few years have seen a vast proliferation in the use of ultrasound to diagnose circulatory disorders. This increasing interest reflects the fact that many tests are non-invasive, reliable, provide bedside answers and do not require large investment of equipment or personnel. Ultrasound systems have been used clinically in two ways. Firstly, ultrasound can provide an anatomical description of underlying tissues and their relative movement by direct echo, with display in one or two dimensions. Secondly, flow and flow patterns in blood vessels or chambers may be studied when the Doppler principle is applied to ultrasound. In practice, echo and Doppler ultrasound are often complementary to each other rather than representing alternatives.

This review summarizes the current status of transcutaneous Doppler ultrasound in the diagnosis of adult and paediatric circulatory disorders, omitting details on technical advances, to concentrate specifically on how this equipment may be applied clinically. Indeed, technical and mathematical information on ultrasound theory is no longer required to degree level physics in order for a clinician to make a reliable bedside diagnosis.

Principle of operation

Transcutaneous Doppler ultrasound systems all utilize an emitting and a receiving transducer, normally combined into one hand-held unit. As ultrasound is poorly transmitted through air, good signals are facilitated by the liberal application of gel between the transducer unit and the skin. The emitting transducer is electrically excited to produce an ultrasonic signal and the beam is directed towards the tissue. The receiving transducer detects

reflected ultrasound and the electronics of the system then measures any frequency difference between the emitted and received sound. Blood cells moving away from the emitted sound will scatter ultrasonic reflections that return to the transducer at a lower pitch relative to the emission. Similarly, blood in vessels conducting flow towards the transducer will return reflections of higher frequency than the emitted sound. Differences in frequency between emitted and received sound are proportional to blood velocity if the angle of the

FIG. 1. The relationship between Doppler shift of frequency, blood velocity and angle of incidence of emitted sound. The Doppler shift of frequency, F_d , produced by a single cell moving at a velocity, V , is given by the equation

$$F_d = \frac{2F_e \cdot V \cdot \cos \mu}{T}$$

where F_e is the frequency of emitted sound, μ the angle of the incident beam to the direction of flow whilst T is the velocity of propagation of sound in the tissue.

With F_e , μ and T as constants then frequency shift becomes directly proportional to blood cell velocity.

incident beam is held constant (Fig. 1). In practice, Doppler systems normally receive velocity information from a finite volume beneath the transducer. As a result, ultrasonic reflections from many

blood cells moving at a range of velocities (and sometimes directions) may be simultaneously received particularly if flow is turbulent. This complex information is generally simplified electronically either by combining all signals to give mean velocity, or by spectral display of the entire range of velocities. The principles governing the use of Doppler ultrasound in clinical diagnosis have been well reviewed by Reid (1978).

Types of Doppler ultrasonic systems

Doppler ultrasound was first used to study myocardial and peripheral blood flow by Satomura (1957, 1959). Since then, the proliferation of applications of Doppler ultrasound in clinical diagnosis has polarized to two main types of systems, continuous wave and pulsed.

Continuous wave systems

The emitting transducer is continuously excited, the reflected sound is received by a second transducer and the instantaneous shift of frequency between emission and reception is determined. This system measures the velocity and direction of blood flow in vessels beneath the transducer but gives no depth information. The earliest systems were non-directional but firstly McLeod (1969), and later Nippa *et al.* (1975) successfully developed systems capable of resolving bidirectional information. The velocity profile across the vessel lumen causes the reception of a spectrum of Doppler-shifted signals which may be processed in several ways (Coghlan and Taylor, 1976) including spectral display of blood velocities (Coghlan and Taylor, 1978).

Pulsed systems

In pulsed Doppler ultrasound systems, one transducer acts both as emitter and receiver. Pulsed bursts of ultrasound are sent out at regular intervals, and the time between successive pulses is used to receive scattered ultrasound. Reflections from different depths are received at different times and by using electronic gating, blood velocity information may be obtained from selected distances along the ultrasound beam, allowing choice of vessel or chamber for study. Much of the early development of pulsed systems is attributable to Baker (1970).

Both pulsed and continuous wave systems have been shown to be capable also of imaging arterial walls and lumen (Mozersky *et al.*, 1971; 1972; Barnes *et al.*, 1976a; Lewis *et al.*, 1978a), although the cost of equipment is prohibitively high. More recently Doppler systems have been combined in single units with real-time ultrasound scanners working in B mode, M mode or 2D. Clinical applications of all these units will be discussed later.

Transmitting frequency

Lower frequencies have a longer range since absorption of sound is proportional to the square of the emitted frequency. However, in practice while peripheral vascular applications optimally utilize ultrasound emission between 5–10 MHz, study of flow within deep structures, notably intracardiac and particularly in adults, often requires transducers with frequencies of 2–3 MHz.

Signal display

Signals may be monitored by oscilloscope, on paper or audibly via a loudspeaker or headphones. Many commercial Doppler systems offer all three simultaneously. A concurrent visual display of the ECG or phonocardiogram is often also necessary.

Many clinical diagnoses at the bedside require the audio output only. Recognition of normal from abnormal arterial and venous velocity sounds needs little practice but represents the corner stone of diagnosis by transcutaneous Doppler ultrasound. Signals may be displayed on paper or oscilloscope either as an average instantaneous blood velocity within a vessel (Fig. 2), or after audiospectral analysis (Strandness and Sumner, 1975a; Coghlan, Taylor and King, 1975; Coghlan and Taylor, 1978). An example of audiospectral output is shown in Fig. 3. The advantage of audiospectral systems is that they provide a simultaneous display of the complete range of blood cell velocities within a vessel. This improvement offers a greater sensitivity to velocity analysis which is particularly useful in diagnosis on the arterial side since flow reversal and turbulence are rendered easier to assess.

Derivatives of the velocity signal

The systolic blood pressure may be directly measured using a sphygmomanometer with transcutaneous Doppler ultrasound as a stethoscope replacement. This is of advantage when examining patients during exercise testing or for assessing systolic pressure in the lower extremities particularly in patients with coarctation of the aorta. Additionally, indirect assessment of cardiac output, pressure gradients and pulmonary arterial pressure (see below) using transcutaneous Doppler ultrasound is now reliable and accurate and often represents important alternatives to catheterization.

With a velocity signal (V) and an estimate of vessel cross-sectional area (A), then flow (Q) along that vessel may be determined from the equation $Q = VA$. However, the measurement of flow by this method using transcutaneous Doppler ultrasound is fraught with difficulties (Strandness, 1978) and must still be considered unreliable at best, although recent experiments with new refinements (Guldvog

FIG. 2. Continuous wave transcutaneous Doppler ultrasound may be used to study changes in the average instantaneous blood velocity within a vessel. In the example shown, forward blood flow in the jugular vein is represented by deflections above the zero line. This patient had tricuspid atresia and primitive ventricle. The triple maxima pattern in jugular venous flow is characteristic of atrial septal defect.

et al., 1980) seem to have resolved some of the problems.

Clinical uses of transcutaneous Doppler ultrasound

Adult

Transcutaneous Doppler ultrasound has been widely used in the diagnosis of many forms of peripheral vascular disease. Satomura (1959) first showed that Doppler ultrasound could be used to describe flow patterns in peripheral arteries. Later Strandness, McCutcheon and Rushmer (1966) and Strandness *et al.* (1967) demonstrated the type of peripheral arterial disorder that might profitably be investigated by this method. The use of transcutaneous Doppler ultrasound in the evaluation of peripheral vascular disease has recently been compared with a number of other non-invasive alternatives by Barnes (1979).

It is also important, whether investigating peripheral arterial or venous disease by transcutaneous Doppler ultrasound, to obtain signals from a similar vessel in the contralateral limb since any difference in velocity patterns in such vessel pairs is likely to be relevant in diagnosis.

Diseases of the arterial system

A. Extracranial arterial disease. A substantial

proportion of cerebrovascular accidents result from atheromatous disease of the carotid artery. The identification of patients in jeopardy needs to be reliable since treatment by end-arterectomy now carries little risk (Thompson and Talkington, 1976). Extracranial arterial disease affecting either branching arteries at the aortic arch, the carotid bifurcation or intracranial vessels can be evaluated by transcutaneous Doppler ultrasound and a number of techniques are now in use.

Periorbital studies. The normal direction of flow in the supra-orbital artery becomes retrograde when the internal carotid artery is sufficiently narrow to produce a pressure gradient promoting collateral inflow to the brain via the external carotid artery. The direction of supraorbital arterial flow has been used by several workers to assess extracranial arterial disease (Muller, 1971; Lye, Sumner and Strandness, 1976; Prichard, Martin and Sheriff, 1979). Consecutive compression of a number of arteries in the head and neck allow deduction of the site of obstruction. The accuracy of diagnosis of these obstructive lesions by transcutaneous Doppler ultrasound has been assessed and has generally compared well with arteriography (Wise *et al.*, 1971; Machleder and Barker, 1972; Lye *et al.*, 1976; Barnes *et al.*, 1977a). The accuracy of the Doppler

FIG. 3. The detection of aortic regurgitation using an audiospectral display of pulsed Doppler signals received (as indicated by the upper M mode display) from the left ventricular outflow tract just above the mitral valve. In the lower Doppler display forward flow into the aorta during ventricular systole is represented by a deflection below the central zero line and the turbulent regurgitant flow is shown as a predominantly positive display in ventricular diastole. The extent of turbulence may be estimated by the vertical scattering in the instantaneous display, and in this case, during diastole, is both above and below the zero line.

technique was also compared with two other non-invasive alternatives for the detection of carotid disease, oculoplethysmography and ocular pneumoplethysmography (McDonald *et al.*, 1978). Of the three, the Doppler examination emerged as the most versatile, portable, convenient and the least expensive.

If, in addition to the direction of flow in the supra-orbital artery, the flow wave shape is also analysed and compared with findings in the common carotid artery (Baskett *et al.*, 1977; Prichard *et al.*, 1979) then diagnostic information may be obtained from the amplitude ratio between the two vessels during systole. It was also pointed out by Prichard *et al.* (1979) that the use of direct percutaneous carotid angiography and arch aortography to identify occlusive carotid artery disease may lead to major (1%) or minor (14%) complications that are not encountered when transcutaneous Doppler ultrasound is used. Further, Crummy *et al.* (1979) found good agreement in the evaluation of carotid obstruction between transcutaneous Doppler ultrasound studies of ophthalmic artery flow and direct carotid arterial imaging, while Otis *et al.* (1979) and Hodek-Demarin and Muller (1979) have discussed possible

pitfalls in assessing some patients with carotid occlusion.

Carotid artery velocity waveform analysis. Carotid artery velocity wave forms vary with increasing levels of stenosis. Applying continuous wave Doppler ultrasound, Rutherford, Hiatt and Kreutzer (1977) showed that these variations in velocity wave form could be used to distinguish normal, stenosed and occluded carotid arteries with 100% accuracy, and they claimed an improvement of sensitivity over the supraorbital Doppler test. They used this system successfully both to select patients for surgery and to demonstrate significant improvement in the carotid artery velocity wave form after endarterectomy.

Reneman and Spencer (1979) have defined and compared Doppler audio spectra in normal and stenosed carotid arteries while Martin *et al.* (1980) have tried to refine this technique further by analysis of the frequency envelope received during Doppler examination of a stenosed carotid artery. Their system improved slightly on earlier techniques by providing a more superior classification of vessel segments. However, the accuracy of diagnosis of carotid artery disease by Doppler ultrasound has

been questioned by a number of groups (Bone and Barnes, 1976; O'Donnell *et al.*, 1980) who found the ultrasound technique alone to be too insensitive to be relied upon and recommended that it be used in combination with oculoplethysmography and carotid phonoangiography. Lewis *et al.* (1980a) have, however, found the Doppler technique ideal for the routine screening of patients for carotid artery disease before open heart surgery since the combination of occlusive disease and reduced blood pressure represents a potential for postoperative complications. Patients with severe carotid artery disease may be diverted to carotid arteriography and endarterectomy before cardiac surgery.

Ultrasonic carotid imaging. The combination of ultrasonic imaging of the carotid artery together with blood velocity measurements by pulsed Doppler ultrasound as a method of diagnosing stenosis or occlusion was compared independently with contrast arteriography by Barnes *et al.* (1976a). The Doppler technique was shown to approximate findings at carotid arteriography in 90% of vessels studied. If present, vascular calcification caused imaging errors, but these could be overcome by spectral analysis of distal carotid velocity signals. Sumner *et al.* (1979), Blackshear *et al.* (1979, 1980) and Hobson *et al.* (1980) have also presented similar results using combined systems displaying pulsed Doppler carotid imaging and velocity patterns, whilst other groups (Spencer *et al.*, 1976; Lewis *et al.*, 1978a; Shoumaker and Bloch, 1978; Lewis, Beasley and Gosling, 1979, 1980; Spencer and Reid, 1979; Weaver *et al.*, 1980) have used continuous wave Doppler systems for the same purpose. The use of pulsed or continuous wave Doppler in this context has been compared by Woodcock (1980) who came to the conclusion that, although both systems provide good results with carotid stenoses greater than 50%, below this level the pulsed system is preferred since it has the ability effectively to resolve in three dimensions. This view is not, however, entirely supported by Miles, Sumner and Russell (1980) who feel that projection errors still cause pulsed Doppler ultrasonic arteriography to miss 20% of carotid stenoses and to misinterpret a further 19%. They found that by linking the Doppler output to a computer to aid imaging carotid vessels, 95% of lesions could be correctly identified.

B. Peripheral arterial disease. The presence of atherosclerotic narrowing, occlusion or aneurysm in the abdominal aorta or peripheral arteries may be diagnosed by transcutaneous Doppler ultrasound. A number of alternative methods have been evaluated, and have been reviewed by Strandness (1978) and Woodcock (1980).

Differential blood pressure measurements to detect arterial disease. Measurement of peripheral blood pressure using Korotkoff sounds during deflation of a proximal cuff has inherent disadvantages. Whilst many arterial segments are physically unavailable to the clinician, this technique also becomes arbitrary at low pressures and distal to occlusions. Sensitivity is greatly enhanced by the use of transcutaneous Doppler ultrasound (Strandness *et al.*, 1966, 1967; Yao, Hobbs and Irvine, 1969; Yao, 1970; Sumner, 1978a). Also, the pressure difference at several points along a limb may be assessed to grade the severity of arterial occlusion (Allen and Terry, 1969). Functional impairment of the circulation due to arterial occlusive disease may be assessed by measuring the ankle pressure response to treadmill exercise (Strandness and Ball, 1964). For patients who cannot walk, the alternative is to stimulate reactive hyperaemia after temporary ischaemia induced by a thigh pneumatic tourniquet (Hummel *et al.*, 1978). However, Fronek, Coel and Bernstein (1978), have pointed out that arterial wall stiffness can produce erroneous results with the use of Doppler ultrasound and have recommended a multisegmental approach to the diagnosis of peripheral arterial occlusive disease. A similar conclusion was reached by Colt (1978) who used ratios of blood pressure taken at various locations to analyse site or sites of obstruction. Baker and Dix (1981) also advised that multiple baseline pressure determinations be obtained on patients if they are to be followed longitudinally.

Velocity waveform analysis in the detection of arterial disease. In normal peripheral arteries there are three peaks of flow in the velocity waveform; systolic forward flow, flow reversal in early diastole and another wave of forward flow in late diastole. Reverse flow may be abolished distal to a stenosis while collateralization tends to reduce peak velocities. Strandness *et al.* (1967) were first to describe some of these changes but diagnosis was later refined by Woodcock, Gosling and Fitzgerald (1972) who timed the propagation of the pulse along arterial segments; this allowed differentiation between various forms of arterial obstruction. Ideally this approach should be combined with the integrated multisegmental pressure measurement and Doppler flow velocity studies recommended by Fronek *et al.* (1978), when a high level of reliability in the assessment of peripheral arterial occlusive disease might be anticipated.

It has been reported recently that stenosis of the iliac artery may be graded by transcutaneous continuous wave Doppler ultrasound recordings taken downstream from the femoral artery (Skidmore *et al.*, 1979; Baird *et al.*, 1980). Ultrasound results correlated well with the severity of iliac stenosis

assessed independently by arteriogram. This group have also reported the use of a Doppler imaging system for the evaluation of lower limb ischaemia in terms of arterial stenosis and luminal narrowing of iliofemoral grafts (Baird *et al.*, 1979).

C. Other arterial applications. Transcutaneous Doppler ultrasound has been used in the sphygmomanometric mode to help select patients for lumbar sympathectomy and to assess their postoperative arterial response (Yao and Bergan, 1973; Seegar, Lazarus and Albo, 1977). A similar system has also been applied to determine the need for sympathetic blockade after frostbite (Rakower, Shahgoli and Wong, 1978), Raynaud's phenomenon (O'Reilly *et al.*, 1979) and to the study of hyperaemia after arterial occlusion and exercise by measuring the systolic pressure ratio between each ankle and the central aorta (Zicot, 1978). Doppler ultrasound has also been of use in assessing the continuity of the palmar arch (Kamienski and Barnes, 1976), screening for arteriovenous fistulae (Barnes, 1978) and arterial trauma (Lavenson, Rich and Strandness, 1971). Haemodynamic complications due to vessel injury at arterial catheterization are also readily assessed in different arteries (Barnes *et al.*, 1973, 1974a, b, 1977b; Barnes, Slaymaker and Hahn, 1977) by transcutaneous Doppler ultrasound, together with the consequences upon flow after insertion of indwelling arterial monitoring catheters (Barnes *et al.*, 1976b). Doppler techniques using sterilized ultrasonic transducers have also been used in the operating theatre to verify patency after arterial reconstruction (Keitzer, Lichti and DeWeese, 1972; Mozersky *et al.*, 1973; Barnes and Garrett, 1978), to localize cerebral (Nornes, Grip and Wikeby, 1979a) and duodenal (Pinkerton, 1979) arteriovenous malformations, saccular aneurysms (Nornes, Grip and Wikeby, 1979b), to assess intestinal ischaemia caused by acute superior mesenteric arterial thrombosis (O'Donnell and Hobson, 1980), or experimentally to measure blood flow in Dacron grafts where the internal luminal diameter is already known (LoGerfo and Corson, 1976). Many of these procedures are of direct benefit to the patient, reducing operative time and excision of uninvolved tissue. The patency of bypass grafts anastomosed between the left internal mammary and the left anterior descending coronary artery in patients with obstructive coronary artery disease may also be assessed using transcutaneous Doppler ultrasound (Benchimol *et al.*, 1978).

Transcutaneous Doppler ultrasound has also proved of benefit by demonstrating that intermittent claudication of the masseter can result from occlusion of the external carotid artery in a patient with generalized occlusive arterial disease (Lewis, Beasley and MacLean, 1978b) and by the demonstration of a

carotid body tumour at the bifurcation (Lewis *et al.*, 1980b). This group have also used Doppler ultrasound to demonstrate changes in the internal carotid artery flow velocity patterns that occur when over-breathing and breath-holding provoke cerebral vasoconstriction or vasodilatation (Beasley, Blau and Gosling, 1979) supporting the earlier results of Miyazaki (1966, 1978) who found that these velocity patterns were also influenced by heart rate, systolic blood pressure, respiratory manoeuvres and vasodilating drugs.

For particular use in patients with psychiatric disorders, hemispheric blood flow may be simply and accurately estimated from Doppler carotid velocity measurements (Risberg and Smith, 1980) with results correlating extremely well with established radiolabelled techniques.

Finally, precise anatomical mapping of vessels is possible using transcutaneous Doppler ultrasound. This application was used by La Grange, Foster and Pretorius (1978) who mapped the course of the subclavian artery in patients to aid accurate introduction of anaesthetic for supraclavicular brachial plexus block. This procedure reduced the risk of pneumothorax and arterial puncture in patients undergoing a wide range of operations and maximized the area of blockade.

Diseases of the venous system

Transcutaneous Doppler ultrasound can be most helpful in the investigation of varicose veins and acute venous thrombosis. In the case of varicose veins, pigmentation and ulcers of the lower leg are insufficient to make a definite diagnosis as these skin changes may also arise from cellulitis, vasculitis or trauma. A Doppler system aids diagnosis by indicating competency of venous valves and also whether there is any flow reversal in the superficial veins. Tests of valvular competence may either be by proximal venous compression or Valsalva manoeuvre (Strandness and Sumner, 1975b) providing a reliable assessment of this condition. Diagnosis of acute venous thrombosis at the bedside is more difficult. Although transcutaneous Doppler ultrasound has several advantages over venography (Strandness and Sumner, 1972), sensitivity and reliability of the former, although generally good, vary considerably from study to study (Barnes, Wu and Hoak, 1975b; Strandness, 1978; Sumner, 1978b; Dosick and Blakemore, 1978; Sumner and Lambeth, 1979). Nevertheless, it is far more accurate (80–95%) than plethysmography (50%) according to recent findings by Hanel *et al.* (1980), although Lepore *et al.* (1978) prefer to combine both approaches and report very reliable results. However, the major advantage of the Doppler approach is that it permits reliable, convenient differentiation of superficial (Barnes

et al., 1976c) from deep venous disease. It also allows discriminative assessment of chronic venous incompetence in superficial (Barnes, Ross and Strandness, 1975), deep (Barnes, 1974) and also perforating (Folse and Alexander, 1970) veins which can, as a result of this diagnosis, be individually ligated via separate incisions reducing the total time in hospital.

Findings comparable with venography have also been reported by Day, Fish and Kakkar (1976) using a transcutaneous pulsed Doppler imaging system. The diagnosis of venous disease using transcutaneous Doppler ultrasound has been well reviewed by Barnes (1978).

Cardiothoracic studies

Since invasive techniques of cardiac diagnosis are expensive, time consuming and risk morbidity, transcutaneous Doppler ultrasound has become an increasingly popular alternative particularly for initial assessment and for routine follow-up. Diagnoses are derived from characteristic changes in arterial, venous or intracardiac velocity waveforms. Such changes may be of maximum peak flow (jets), flow direction, pulsatility or nature of flow (laminar or turbulent). The use of Doppler ultrasound in the diagnosis of many cardiological problems, particularly valvar is often similar in the paediatric and adult patient.

Johnson *et al.* (1973) first reported that Doppler ultrasound could be used to help diagnose murmurs due to aortic and mitral stenosis and regurgitation, left ventricular outflow tract obstruction, tricuspid and pulmonary stenosis, pulmonic insufficiency, coarctation of the aorta and atrial septal defect. They found a striking similarity between the Doppler findings and intracardiac phonocardiography and showed, therefore, that murmurs could be precisely located using an external sensor. This group then went on to show that Doppler systems tend to complement rather than duplicate echocardiographic M-mode information particularly in helping to diagnose valvar and septal defects (Baker, Rubenstein and Lorch, 1977). Indeed, it is a more specific and sensitive technique for the detection of regurgitant jets at the aortic and mitral valves than standard echocardiography (Ward, Baker and Rubenstein, 1977). There is also some evidence that measurement of jet velocities may permit estimation of the pressure gradient driving them. The application of Doppler ultrasound in cardiac diagnosis has previously been reviewed by Baker (1978).

With transcutaneous Doppler ultrasound, the choice of emitting frequency is important for intrathoracic studies (see above), and the system must have good spatial resolution or flow in adja-

cent vessels will interfere with the examination. Also, ultrasonic windows free of intervening lung tissue must be used since the beam is poorly transmitted through air.

One of the main advantages of using Doppler ultrasound in cardiac diagnosis is that it can easily differentiate multiple areas of disturbed flow whereas loud harsh systolic flow murmurs on auscultation may prevent the detection of softer yet important murmurs due to mitral or tricuspid regurgitation.

Aortic regurgitation. The diagnosis of aortic regurgitation by transcutaneous Doppler ultrasound may be achieved by direct sonication of the aorta (Thompson *et al.*, 1970). The technique has since been refined to allow regurgitation to be graded as mild, moderate or severe with some confidence (Boughner, 1975; Ward *et al.*, 1977; Sequeira and Watt, 1977; Ciobanu *et al.*, 1980). Excessive diastolic reverse flow in the more accessible subclavian artery has also been shown to be indicative of aortic regurgitation (Tunstall Pedoe, 1971) with a diagnostic accuracy of 85% and is particularly useful in patients with unstable or progressive aortic regurgitation (Tunstall Pedoe, 1974a). Large vortices in aortic flow may render the subclavian method more reliable in some patients. Lorch *et al.* (1977) have used pulsed Doppler ultrasound to follow the diastolic regurgitant jet from the valve orifice, via the outflow tract, down into the main body of the left ventricular chamber. Recent results (Quinones *et al.*, 1980) have shown a 94% accuracy in the diagnosis of aortic regurgitation by Doppler ultrasound.

Aortic stenosis. A jet of systolic turbulence can be detected by ultrasound within and above the aortic valve in aortic stenosis (Tunstall Pedoe, 1974b; Lorch *et al.*, 1977), with Doppler shift in diastole becoming zero with cessation of flow. Young *et al.* (1980) have reported a 92% accuracy in detecting aortic stenosis by transcutaneous Doppler ultrasound and regard it as an excellent screening technique since, unlike other methods, diagnosis is unaffected by the presence of aortic insufficiency, old age or left ventricular failure or dilatation. Richards *et al.* (1980) have also reported that Doppler ultrasound identifies aortic stenosis and more accurately estimates its severity than M-mode or 2D echocardiography. The pressure drop across an aortic stenosis may also be estimated non-invasively by using Doppler ultrasound to measure the maximum jet velocity (Hatle, Angelsen and Tromsdal, 1980). Accurate assessment of aortic stenosis, regurgitation and prosthetic function using pulsed Doppler ultrasound has recently been reported by Veyrat *et al.* (1980).

Mitral regurgitation. This is detected in the outflow tract of the left atrium during ventricular systole (Johnson *et al.*, 1974b; Lorch *et al.*, 1977). Severity of regurgitation may be assessed by the amplitude and duration of reverse flow. Diebold *et al.* (1979) found that diagnosis of this condition was easier and more accurate using a parasternal approach rather than from the apex, although recently Quinones *et al.* (1980) achieved a 94% diagnostic reliability using Doppler ultrasound from the apical position. However, if Doppler ultrasound is combined with 2D echocardiography, still more sensitivity is achieved since, apart from improved analysis of the regurgitant flow, a characteristic vibration of the mitral valve may also be detected (Miyatake *et al.*, 1980). Nevertheless, Blanchard *et al.* (1980, 1981) have since reported a 100% accuracy in diagnosing mitral insufficiency by Doppler ultrasound alone, while Abbasi *et al.* (1980) report a sensitivity of 92%.

Mitral stenosis. In mitral stenosis, turbulence occurs during diastole just posterior to the mitral valve in the left atrial outflow region, within the mitral valve orifice and in the left ventricular inflow region (Lorch *et al.*, 1977; Kalmanson *et al.*, 1977). Doppler ultrasound is capable of detecting at least three distinct flow patterns relating to different mitral valve gradients (Diebold *et al.*, 1979) although atrial fibrillation affects the diagnosis of mild stenosis. Holen and Simonsen (1979) also found Doppler ultrasound to be sufficiently accurate (compared with left ventricular catheterization) to be used for the assessment of pressure gradients in the diagnosis of mitral stenosis. Hatle *et al.* (1978), Hatle, Angelson and Tromsdal (1979) and Thuillez *et al.* (1980) have derived ultrasonic Doppler techniques for assessing patients with combined mitral stenosis and regurgitation. Additionally, measurement by transcutaneous Doppler ultrasound of the mean diastolic pressure gradient across Bjork-Shiley mitral valve implants has similarly been reported by Holen, Simonsen and Froyssaker (1979).

Tricuspid regurgitation. Tricuspid regurgitation is associated with turbulent flow during ventricular systole, and the disturbed flow pattern is similar to that in mitral regurgitation (Lorch *et al.*, 1977) and hence may also be assessed by transcutaneous Doppler ultrasound. If guided by 2D echocardiography, the Doppler technique can be used to grade severity of tricuspid regurgitation (Sakakibara *et al.*, 1980) with a consistency close to angiography. However, even without the benefit of 2D echocardiography, Doppler ultrasound detection of tricuspid regurgitation appears superior to M mode alternatives (Waggoner *et al.*, 1981).

Possibly derangements of jugular venous flow

provide the simplest means of diagnosing tricuspid regurgitation (Sivaciyan and Ranganathan, 1978).

Tricuspid stenosis. Velocity wave patterns detected by Doppler ultrasound show turbulence in diastole and findings are similar to mitral stenosis (Lorch *et al.*, 1977).

Pulmonary regurgitation. This may be diagnosed by Doppler ultrasound on the basis of turbulent reverse flow in the right ventricular outflow tract during diastole (Lorch *et al.*, 1977). Velocity patterns are similar to those in aortic regurgitation and recent results suggest diagnosis by Doppler ultrasound to be very reliable, sensitive and specific (Waggoner *et al.*, 1981).

Pulmonary stenosis. This may be characterized using transcutaneous Doppler ultrasound by a jet of systolic turbulence in the proximal pulmonary artery (Lorch *et al.*, 1977; Goldberg *et al.*, 1979b). Velocity patterns are similar to those in aortic stenosis.

Estimation of pulmonary arterial pressure. Jugular venous flow velocity waveforms appear sensitive to the level of pulmonary hypertension (Sivaciyan and Ranganathan, 1978) but as yet no accurate and reliable technique for the estimation of pulmonary arterial pressure has been reported using this approach. Two groups have, however, recently shown that a value for pulmonary arterial pressure may be derived non-invasively by transcutaneous Doppler ultrasound: Foulst *et al.* (1980) measured right ventricular systolic time intervals and flow velocity to estimate mean end diastolic pulmonary arterial pressures achieving good correlations with standard pressure measurements and also finding the method sensitive to acute changes in pulmonary arterial pressure; Hatle *et al.* (1981) estimated pulmonary arterial systolic pressure in patients with pulmonary hypertension also using a Doppler technique to measure systolic time intervals. Their technique is based on the assumption that the duration of the interval between pulmonary valve closure and tricuspid valve opening increases proportionally with pulmonary arterial systolic pressure. The method appeared to correlate well ($r=0.89$) with direct pressure measurements. Unpublished independent assessment of this method in other centres currently seems to validate this approach with the proviso that the systolic time intervals may be more accurately measured if 2D echocardiography is used to provide a simultaneous image of the two valves.

Functional assessment of the myocardium. Transcutaneous aortovelocity using Doppler ultrasound can be used to measure aortic systolic ejection times and indices (acceleration, deceleration and peak velocity). Work in this area was pioneered

and later reviewed by Light (1969, 1976). The technique was shown to be simple and reproducible both in adults and children (Fraser *et al.*, 1976), while clinically, changes in stroke volume, phasic flow velocities and cardiac output monitored by this method have been shown to compare well with invasive measurements (Sequeira *et al.*, 1976). Central blood flow may also be assessed whilst the instantaneous velocity waveform gives further information on left ventricular function and sympathetic drive in the critically ill patient (Buchtal, Hanson and Peisach, 1976; Bilton *et al.*, 1978; Hanson and Bilton, 1978). The value of aortic systolic ejection indices were found by Gardin *et al.* (1980) to be sensitive to left ventricular dysfunction in patients with dilated cardiomyopathy.

Cardiac output has been estimated in patients without valvar stenosis by the combined use of Doppler and 2D echocardiography (Bommer *et al.*, 1980; Magnin *et al.*, 1981) with respective correlation coefficients of 0.85 and 0.83 when compared with invasive studies. Even better correlation with invasive methods ($r=0.96$) have been reported by Darsee *et al.* (1980a) and Darsee, Watter and Nutter (1980b) who have combined Doppler methods with M mode echocardiography.

Systolic time intervals may also be measured by Doppler ultrasound and Rothendler, Schick and Ryan (1981) have recently described a highly accurate modification enabling these to be measured whilst patients are exercise testing.

Recent experimental results using Doppler ultrasound to measure beat-by-beat changes in stroke volume (Steingart *et al.*, 1980) are not sufficiently reliable at present to provide clinically useful information.

Paediatric

Transcutaneous Doppler ultrasound has found a number of invaluable applications in paediatric and fetal (McCallum *et al.*, 1978) diagnosis. Signals from Doppler systems are perhaps easier to record in children because of the shorter distances between transducer and vessel; however, this often also means that a different ultrasonic transmitting frequency must be used in view of the reduced range. The majority of techniques relate to diagnosis and assessment of congenital heart disease since peripheral vascular problems are uncommon at an early age although Doppler ultrasound has been used to diagnose neonatal asphyxia and intraventricular haemorrhage by monitoring flow in the anterior cerebral arteries (Bada *et al.*, 1979).

Blood pressure and coarctation

The measurement of blood pressure in children is greatly facilitated by the use of transcutaneous

Doppler ultrasound and cuff. This technique is accurate (Hernandez, Goldring and Hartman, 1971; Black, Kotrapu and Massie, 1972) and may be used to measure blood pressure conveniently in older children during exercise testing. The fact that values for systolic blood pressure in infants and young children measured by Doppler ultrasound correlate well ($r=0.88$) with simultaneous invasive determinations (Whyte *et al.*, 1975) has permitted a non-invasive longitudinal study of the changes in blood pressure in a large number of normal children in the four years after birth (de Swiet, Fayers and Shinebourne, 1980). Doppler ultrasound is also particularly useful in the lower extremities of neonates with coarctation of the aorta where the stethoscope is often unreliable. Doppler ultrasound can be used to assess temporal elongation of systolic flow in the femoral artery due to collateral flow in patients with coarctation of the aorta and it may be of value to use Doppler to determine the direction of blood flow in each costal artery to help assess the precise location of the abnormality.

Shunts

Kalmanson *et al.* (1972) first used Doppler ultrasound directed at the jugular vein to diagnose atrial septal defects and to assess shunt volume. This technique is reliable only when patients are in sinus rhythm (Kalmanson, Veyrat and Chiche, 1970). Jugular venous flow can also be used to diagnose ventricular septal defects (Kalmanson *et al.*, 1974) with some additional indication of the size of the shunt and the degree of pulmonary hypertension.

Rather than using the jugular venous approach, it is perhaps now easier to detect septal defects by the turbulence they produce in cardiac chambers. Large gradients result in severe turbulence. Whilst flow across an atrial septal defect is almost always inaudible, it may usually be detected and analysed using Doppler ultrasound (Johnson *et al.*, 1976; Goldberg *et al.*, 1978). Johnson *et al.* (1974a) also previously managed to thread the Doppler sample volume through ventricular septal defects and along the resultant jet; indeed, this is often possible with perimembranous ventricular septal defects and localization of systolic turbulence both in the right ventricular outflow tract and the interventricular septum will reliably differentiate this lesion from infundibular pulmonary stenosis. The detection of systolic jets both in the right ventricular cavity and the interventricular septum due to muscular ventricular septal defects is less reliable than when the defects are membranous. Stevenson, Kawabori and Guntheroth (1977) used Doppler ultrasound to differentiate ventricular septal defect from mitral regurgitation which often present with similar

apical systolic murmurs. A 90% accuracy in the diagnosis of ventricular septal defect by transcutaneous Doppler ultrasound has since been reported (Stevenson *et al.*, 1978).

Stevenson, Kawabori and Guntheroth (1979a) have shown that in patients with patent ductus arteriosus, it is possible to distinguish those with from those without pulmonary hypertension using pulsed Doppler ultrasound. Estimation of the magnitude of flow through the ductus has been made using Doppler ultrasound by Serwer, Armstrong and Anderson (1980).

Evaluation of flow in conduits is also possible after surgery for cyanotic congenital heart disease using transcutaneous Doppler ultrasound. Patency in systemic to pulmonary arterial anastomoses has been confirmed in this way by Allen *et al.* (1979) and their technique provides a simple, routine and long-term non-invasive method of assessing these shunts. Conduits inserted during the Fontan or Glenn procedures are also highly amenable to this approach, and their patency may easily be assessed longitudinally by routine examination using transcutaneous Doppler ultrasound.

Valvar defects

The diagnosis of these defects in children is similar to the investigation of valvar stenosis and incompetence in adults described earlier. The differential diagnosis of mitral regurgitation from ventricular septal defect was reported by Stevenson *et al.* (1977). The diagnosis of valvar defects has been elegantly refined for paediatric use by Goldberg *et al.* (1979a, 1979b) with a fine appraisal of problems and pitfalls. It is also possible to differentiate atretic from stenosed pulmonary valves in the newborn without catheterization by the combined use of Doppler ultrasound and 2D echocardiography (Korfhagen, Meyer and Kaplan, 1981).

Transposition

A method of diagnosing pulmonary outflow tract obstruction in complete transposition of the great arteries using pulsed Doppler ultrasound has been described by Areias *et al.* (1978). Since catheterization is difficult in these patients, and M mode echocardiography is not well suited for the evaluation of these rings of muscular stenosis, the Doppler approach is of great benefit particularly since developing stenosis may be monitored as often as desired. Catheterization may also be avoided by using Doppler ultrasound in patients whose great vessels are neither normal nor suggestive of transposition (Stevenson *et al.*, 1980). In these patients, detection of flow in the patent ductus arteriosus may be used to define the pulmonary artery and help diagnose the presence of transposition.

Two of the major operative alternatives for transposition of the great arteries, Mustard's and Senning's repairs, involve atrial surgery. Using transcutaneous Doppler ultrasound to monitor jugular flow, it has been demonstrated by Wyse *et al.* (1980) that, whilst both operations compromise atrial volume and compliance, this is far less severe after the Senning operation. Also, obstruction to atrial inflow is an important cause of late morbidity and mortality after Mustard's operation and two methods have been reported for its detection by transcutaneous Doppler ultrasound (Stevenson *et al.*, 1979c; Wyse *et al.*, 1979). As obstruction may sometimes be severe or total yet remain asymptomatic, these methods provide an important yet rapid screening process for patients operated on for transposition of the great arteries. If available, 2D echocardiography may also be used to show obstruction either by direct visualization of the systemic venous atrium or by venous injection of saline to display whether microbubbles can pass unhindered from the superior vena cava to the atrium or whether they must alternatively follow a collateral route via the azygos and hepatic veins to the inferior vena cava.

Total anomalous pulmonary venous drainage

Pulsed Doppler ultrasound has been used not only to diagnose total anomalous pulmonary venous drainage (Skovranek *et al.*, 1980) but also to provide a unique, specific and non-invasive method of differentiation artefacts from true anomalous pulmonary venous return to a left superior vena cava (Stevenson *et al.*, 1979b).

Conclusion

Transcutaneous Doppler ultrasound is a safe, non-invasive diagnostic tool. Its uses have proliferated dramatically in the last few years largely because tests are simple, quick, atraumatic, and in many cases less expensive and more reliable than invasive alternatives. Its role in the diagnosis of circulatory disorders is liable to continue to increase over the next few years as more centres and general practitioners turn to Doppler alternatives.

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