DOPPLER/ECHOCARDIOGRAPHY
THE LANCASTER EXPERIENCE

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SUMMARY

The Doppler/echocardiography technique for non-invasive cardiac investigation is described with details of both the principles used and the difficulties involved. No attempt will be made to give a comprehensive account as space is limited, but hopefully some appreciation of the technique will be acquired. A description of the Lancaster service is given. The high standard of the equipment and the experience of the staff, means that the local service is accepted as equal to that of the major cardiological centres in adult cardiology.

HISTORICAL BACKGROUND

Non-invasive estimation of the heart by ultrasound techniques has changed considerably since its inception. There are now two main components in the modern technique of Doppler echocardiography. One is based on conventional echo sounding and the other utilizes the Doppler principle.

Echocardiography or cardiac ultrasound was developed from the radar and naval sonar used in World War II to detect objects such as submarines. As it was classified information it was after the war before engineers were allowed to use it for research. Medical interest grew from this. Hertz and Edler in Sweden began to use it in 1953, detecting only the pericardium and later the anterior mitral valve leaflets. The Americans became involved in 1957 (Reid and Joyner). By 1961 reports had appeared on the detection of mitral stenosis, left atrial tumours, aortic stenosis and anterior pericardial effusion. The Japanese became interested in two dimensional echo (2D Echo) in 1962. Feigenbaum (USA) in 1963, becoming ‘frustrated with the limitations of cardiac catheterisation and angiography’, felt that the new technique could possibly overcome this. Simultaneously, use of the Doppler principle in plotting and estimating flow of blood through the heart was being developed.

The Doppler principle, named after Christian Johann Doppler (1842), who in his investigations in astronomy noticed that a shift in the frequency of light gave rise to a change in colour, felt it also applied to sound. The principle was used more generally by the Japanese in 1955. In 1960, and then together with the Americans in 1961, they started to utilise Doppler to study blood flow. Holen of Norway (1976), followed by Hatle and Angelson from Trondheim, Norway, further developed the use of Doppler particularly with the use of the continuous wave transducer. They laid down a group of concepts concerning pressure gradients that are still being used today.

The main breakthrough came with the concomittant development of the electronics industry and computers, eg the ability to time share the pulsed Doppler and the echo signals in a single crystal (1970). Computerisation of the Fourier theorem using linear frequency analysis devices to produce commercial digital Fast Fourier Transform in the early 1980s, allowed simultaneous analysis of the various frequency components. This was used to analyse the spectral display and give accurate linear analysis of velocity curve profiles. The development of multigate Doppler in 1979 later led to commercial colour flow mapping in the late 1980's.

PHYSICAL PRINCIPLES

Though both the Doppler and echocardiography techniques utilise ultrasound (a frequency range from 1.9 to 7.5 MHz is commonly used in cardiology), the way it is used and the techniques are different. With the echo the ultrasonic wave hits the target or interface between two materials with different acoustic impedance at right angles and is reflected back to be picked up by the same crystals that emitted the sound. Using echo, the anatomy, size and function of the heart can be displayed in real time.

The Doppler principle is defined as an apparent shift in transmitted frequency as a result of motion of either the source or the target, eg a train whistle appears to rise in pitch as the train moves towards the observer. In cardiology it is used to determine the motion of the red blood cells relative to the transducer. The same crystal source that produces the echo is used, but the sound is required to travel parallel to the flow of blood. Reflection of ultrasound from the blood cells is usually too low to be detected by echos but the Doppler technique can detect these low amplitude signals.

The source, the transducer, is stationary and the target, the red blood cells, are in motion. The received frequencies are compared with the transmitted frequency. The Doppler shift is directly proportional to the velocity of the red blood cells. The difference in frequency produced falls within the human audio range and the ear can be used to ascertain the highest frequencies. This is a very important part of the technique and often not appreciated as such. Laminar flow has pure tones. Disturbed flow with its different frequencies has a rough sound. The sound is distinctive and the spectral envelope on the display has a well defined edge.

A knowledge of fluid dynamics is needed to understand the possible artefacts and what is needed to avoid them. It is very angle-dependent; to get the correct velocity it is important to get the angle of incidence below 20° and preferably close to zero as possible. It is position-dependent which means that the patient must be moved around in order to obtain a good reading which is also true of the echo technique.
Doppler also gives directional information. Direction of flow is displayed with reference to the direction of the received beam. Blood moving towards the transducer is displayed above the baseline, that moving away from it, below the baseline. Thus Doppler shows jet origin, direction, velocity and projection. It is used to calculate gradients across orifices, estimate regurgitant jets, ascertain pressures in chambers and vessels and assess diastolic function.

There are three main ways of using Doppler. Pulsed wave (PW, continuous wave (CW) and colour flow mapping (CFM). The PW and CFM differ from the CW in giving the distance from the transducer and the site of the heart being interrogated. With the PW the operator can locate exactly the area to be studied and only information from that site will be displayed both as a velocity graph against time and as an audio signal. However this is depth limited as the maximum velocity is dependent on how rapidly the information is sampled: this is called the pulse repetition frequency. The depth limitation is overcome by using the CW technique. Velocities as high as 8m/second can occur in the heart and only the CW can record this. Maximum velocity with the PW is around 2m/second or less depending on depth.

CFM is only multigated PW where the information is acquired at many individual points along the ultrasound beam. Therefore information from several hundred points is required to generate one pixel. PW and CW using the Fast Fourier Transform take about 5 milliseconds to analyse one pixel. As there are several thousand pixels it would not be possible to do this for all the pixels in one image. So a technique borrowed from radar, called autocorrelation, is used in which a mean value is calculated for each pulse, ie it does not require calculation of many hundreds of samples to generate one pixel. The mean value is then assigned a particular colour. Like PW it is depth limited. In essence it is a qualitative rather than a quantitative technique and gives a coarse spatial distribution of velocity. But the latter is very dependent on the driving pressure at a valve, eg of the left ventricle in mitral regurgitation, rather than on the volume. Also manufacturers differ in the way they display CFM and factors such as gain and pulse repetition frequency can affect the display and give erroneous display of colour change (aliasing). So for many reasons it is not an accurate technique. At best it is only a rough technique and very operator-dependent.

Therefore all three Doppler techniques have to be used in conjunction with each other for accurate estimation and serial studies.

LOCAL SERVICE

The Lancaster service started with phonocardiography in 1961. A simple echocardiograph was added in 1974 (Fig 1), 2D echo in 1977, pulsed and continuous wave Doppler in 1984 and colour flow mapping in 1989 (Fig 2). Again, as in the historical development, in 1974 detection was confined to the mitral and aortic valves and the pericardium. Gradually with experience and improving equipment the technique has been developed and a fully comprehensive assessment of cardiac pathology is now available which can be an adjunct to cardiac catheterisation. Development is such that it has been suggested that in the hands of an experienced operator from a laboratory with a reliable reputation, surgery can be carried out in certain cases (eg aortic and mitral stenosis) without prior catheterisation.

Fig 1 – The first echocardiograph in Lancaster. This Smith Kline Ekoline recorder was only capable of recording simple M-mode echoes. Each time an image was captured the display was photographed with a Polaroid camera (not shown). A time-consuming procedure which improved with the advent of chart recorders.

The technique, however, particularly the Doppler, is very operator-dependent and requires considerable practice, and a degree of scepticism based on the understanding of cardiac haemodynamics, pathology and also the principles of the various techniques including their limitations. Not all patients give good recordings though with each electronic upgrade this is slowly improving with time.

Patients are referred to the Day Investigation Unit of the Royal Lancaster Infirmary, from a wide area (population approximately 200,000) via the consultant staff. The recordings are made in a purpose-designed unit which has a pleasant, calm atmosphere. The relaxed ambience is not appreciated by the patients but needed to try to reduce the incidence of tachycardia which can make measurements difficult if not impossible. In some units sedation is used for children. It is a good sign when patients fall asleep. However any gradient quoted is the gradient at rest at a certain cardiac output. This makes it difficult to compare results accurately on the same patient from different centres as the basal conditions may not be the same eg patients may be frightened by cardiac catheterisation. Cardiac output is increased with exercise, anxiety, fever, anaemia, pregnancy and tachycardia.

High temperatures, noise and light are particular problems. The computers produce the equivalent of a 3 KW heater and the heat can induce tachycardia. However noise, eg as from air conditioning, can obscure the Doppler sound and it is very important that the audio signal can be heard as
it is used to 'tune' to the correct velocities. The gain settings have to be set carefully to define accurately the cardiac borders and bright lights can affect the screen display. Therefore a darkened area is required. This can be difficult to obtain on the wards where suitable curtaining rarely exists.

There are two echocardiographs. The major machine is a Hewlett Packard-77020AC upgrade CF (K) which in December of this year will be upgraded to revision N. This will produce very detailed, high quality, real time echos in all formats with Doppler to the industry standard (Vingmed). It is locally mobile only. A smaller portable Hewlett Packard Sonos 100 machine is also available which can be moved to more inaccessible sites and can even be dismantled and carried by car to distant hospitals. This machine is suitable for simple recordings and as an emergency stop gap. Ideally all patients should have access to the HP77020AC recorder with its much more powerful computers and detailed display.

The technique requires continuous practice, particularly the Doppler. In addition there is a continuous upgrade process to keep abreast of the electronic developments, and also a continuous training programme.

In parallel with the development of cardiac ultrasound there has been a change in the epidemiology of heart disease. Rheumatic valve disease now has a very low incidence, ischaemic heart disease has come to the fore and very soon those that have benefited from the surgical developments in treating congenital heart disease will reach the adult cardiologists. Training programmes have to take account of this to maintain a quality service.

There is an emergency service though this is rarely needed. Experience has shown that it is usually required for acquired ventricular septal defects (VSD) in acute myocardial infarction or tamponade due to pericardial effusion. Reporting is instantaneous due to the presence in the department of a doctor trained in the techniques. Only a diagnosis is made, future clinical management resting with the referring physicians or the cardiologist. If the reporting doctor feels treatment is urgently required this is organised.

**TECHNIQUE**

When the patient is referred details are required of the provisional or definitive diagnosis and specific questions to be answered. Also details of the clinical examination, auscultation, haemoglobin, chest X-ray and ECG. This is necessary as Doppler echocardiography is a haemodynamically-based technique.

The valves must be interrogated from any position which allows the very acute angle of less than 20° and hence the correct velocity. This position is limited by bone which absorbs ultrasound and lung where the air scatters it. The aortic valve, for instance, can be studied from the apical, subxiphoid, suprasternal and precordial areas and all areas should be attempted with each patient. The technique is time consuming and dependent on the degree of skill of the operator and the number and types of lesions present. It can take up to three-quarters of an hour. It is not a technique to be ordered at will as it is relatively expensive and time consuming. It should be part of carefully thought out series of investigations.

The echocardiographers must be aware of conditions that can affect the recordings, such as an increase or reduction in the cardiac output. Aortic stenosis could be underestimated due to the lowered velocity across the valve in patients with cardiac failure. If aortic regurgitation is detected but has not been suspected on auscultation, this has to be taken into account is it could over-estimate the degree of aortic stenosis if present. There has to be the ability to 'think on one's feet' during the recording, if necessary to change the diagnosis and certainly to give additional information.

Frequently there is more than one pathological process such as hypertension and ischaemic heart disease and/or aortic valve disease, and the effects of all have to be estimated. A not infrequent enquiry is 'could the blackouts be due to the aortic stenosis or could they be due to the ischaemic heart disease?' 'Is the left ventricular hypertrophy due to a pathological process or the result of his athletic activities?' There can be the unexpected discovery of a mural thrombus in an akinetic left ventricular apex or a healed vegetation on a valve or a left atrial myxoma, hypertrophic obstructive cardiomyopathy, or even amyloid disease.

Pathological problems such as orifice shape and direction of the jet can also affect the Doppler. The image displayed is a 2D image but the cardiac structures are three dimensional and change shape with time. The stenotic orifice may not be shallow but form an irregular shaped tube or there may be spray formation at the orifice. These can affect the velocities. The technique is not directly comparable with cardiac catheterisation as in the latter case different pressure measurements are made and regurgitation is estimated by persistence of dye in the receiving chamber.

Flow disturbance may extend to another area of the heart eg a VSD may cause a flow disturbance in the pulmonary artery and suggest pulmonary stenosis is present even though
it is not. On the other hand masking may occur when the flow is disturbed by one obstruction and yet when the flow passes through a second obstruction it is not changed; therefore the latter is missed.

CASE HISTORY

The following case history will illustrate some of the points that have been raised:

A female aged 73 years, presented with dizziness and two syncopal episodes. There were no complaints of chest pain or dyspnoea but the patient was very frightened and inactive, taking very little exercise. Examination did not reveal any cardiac failure. The blood pressure was 110/90, with a slow rising pulse (rate 60 beats per minute) and systolic thrill at the second right intercostal space (2R). Auscultation revealed absent first and second heart sounds and a grade III ejection systolic murmur maximum at 2R and conducted to the carotids. A diastolic murmur was not heard. The haemoglobin was 12.7g/dl; the ECG showed left bundle branch block and left ventricular hypertrophy, and the chest X-ray showed gross cardiomegaly. An initial diagnosis of aortic stenosis was made.

Fig 3 - Long axis, left sternal border echo showing the calcified aortic valve, posterior mitral annulus calcification and hypertrophied interventricular septum.

Abbreviations: AV = aortic valve, LA = left atrium, IVS = interventricular septum, RV, LV = right and left ventricle, MC = posterior mitral annulus calcification, MV = mitral valve.

Echocardiogram: This confirmed the diagnosis by showing a heavily calcified aortic valve with no leaflet movement (Fig. 3). The cardiomegaly was due to marked left ventricular hypertrophy with a normal cavity and contraction. The left atrium was slightly enlarged, the right atrium, ventricle and the other three valves were normal though posterior mitral mitral annulus calcification was present. The latter can cause mitral stenosis.

Doppler: Multiple position PW and CW recordings obtained a velocity of 5.5m per second across the aortic valve (Fig. 4) and, as there was no evidence of cardiac failure or aortic regurgitation, the systolic gradient was 121 mmHg and the left ventricular pressure was 231 mmHg. PW, CFM showed mitral regurgitation, the jet extending two thirds of the way into the left atrium. CW showed the moderately intense jet to have a velocity of 5.4 m per second. PW did not show any evidence of mitral stenosis. Left ventricular diastolic function was abnormal. Mild tricuspid regurgitation was also present. It was not possible to estimate pulmonary artery pressures.

Fig 4 - CW Doppler showing the signal obtained from the aortic valve (velocity against time). The record was taken from the apical area in the left lateral position. The systolic velocity is 5.5m/second and displayed below the baseline as the direction of flow was away from the transducer.

The diagnosis was severe aortic stenosis with secondary moderately severe mitral regurgitation. The patient refused surgery and died suddenly eight months later.

Post mortem examination showed severe aortic stenosis. The valve was bicuspid and heavily calcified. There was also marked left ventricular hypertrophy. The other valves were normal and the lungs were oedematous.

THE FUTURE

Research is being carried out on tissue characterisation, which is at present very limited; contrast echocardiography using agents containing microbubbles that can be injected via a vein and will pass through the pulmonary bed to outline the left side of the heart; systolic and diastolic function. For the latter very powerful computers are needed. Three dimensional recordings may be available in the next twelve to eighteen months.

The next development is ‘edge detection’. It has been found that the engineers can differentiate between the tissues of the heart and the flow of blood and as a result have developed ‘edge detection’ techniques. For the first time it may be possible to calculate the ejection fraction in real time. The cardiologists are now considering other possibilities. This shows the close interrelationship required between electronic engineers and the cardiologists. The information is there – it is just a question of how to acquire and use it to enhance detection and diagnostic techniques.

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