Imaging the Heart

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The range and sophistication of the techniques available for imaging in all areas of medicine have increased dramatically over the last 20 years at a rate which is itself increasing. Twenty years ago the predominant techniques for cardiac imaging were plain and contrast radiography. Cardiac ultrasound and nuclear imaging techniques were then in the early stages of development but these two approaches now provide detailed and reliable anatomical and functional information on the heart, and new techniques such as digital vascular imaging, computed tomography, nuclear magnetic resonance and positron imaging now give detailed cardiac images of a quality which could hardly have been thought possible some years ago. The principal driving force in all this has been the developing technology of micro-electronics. Equipment has become smaller, cheaper and more reliable. Most modern imaging devices incorporate microcomputers which permit the use of image processing techniques. Such techniques require large amounts of computer memory, the cost of which has fallen to a value approximately \( \frac{1}{200} \) of its equivalent eight years ago.

In dealing with a subject which is advancing so rapidly, it is inevitable that this article will soon be outdated. Nevertheless, the rate of progress will not be geographically uniform; because of the high cost involved, research in these areas will be at relatively few centres. Other medical centres will not wish to commit limited funds to techniques of unproven reliability, uncertain value or prohibitive cost.

Problems Common to all Types of Imaging in Cardiology

Because of its location and function, there are special problems in imaging the heart. Its location on the superior surface of the diaphragm results in upward and downward movement with respiration. Its function requires it to change shape and volume during each cardiac cycle. The ventricles change in shape, but not in volume, during the isovolumetric phase of diastole and thereafter increase in size continuously, but not at a uniform rate, until the end of diastole. During the isovolumetric phase of systole they change in shape but not in volume. During the ejection phase of systole the volume of each ventricle falls. The atrial volume changes are even more complex. Atrial filling occurs continuously, but not uniformly, throughout ventricular systole and diastole, and atrial emptying occurs predominantly at two periods—follow-

ing the opening of the atrio-ventricular valves when some 70 per cent of atrial emptying occurs and in association with atrial contraction when some 20 per cent of atrial emptying occurs. It follows that if imaging techniques are to give information on cardiac function or on the selective anatomy of the cardiac chambers, attention must be paid to the phase of the cardiac cycle in which the imaging data are collected.

In addition to physical movement associated with respiration and with the cardiac cycle, the heart is displaced by changes in body position.

Techniques currently available for Cardiac Imaging

The two prime objectives of cardiac imaging are to display the anatomy and function of the heart and a common secondary objective is to demonstrate the inter-relationship of the two. Some imaging techniques (e.g. ionic tracer scanning) also demonstrate the viability of the myocardium.

The plain Chest X-ray

The plain chest X-ray gives information on the overall cardiac size, limited information on selective chamber enlargement, information on the pulmonary circulation and on abnormal radiological findings such as calcification[1] (Fig. 1). This very basic cardiac imaging technique is available wherever cardiac investigation is undertaken and need not be considered any further here.

Contrast Radiography with Selective Chamber Opacification

Contrast angiographic techniques (with selective chamber opacification by vascular and cardiac catheterisation techniques) provide high definition, high resolution images of the left ventricle, aorta, left atrium, pulmonary artery and coronary arteries and of any abnormal structures such as a ventricular aneurysm, an arterial or arteriovenous fistula or a ductus arteriosus. In the demonstration of all these features contrast angiography with selective chamber opacification provides the gold standard against which all other imaging techniques must be judged. The extremely high quality of the images produced is bought at the cost, to the patient, of a highly invasive approach and, to the institution, of expensive apparatus. These two drawbacks limit the usefulness of the technique to those patients fit enough to undergo the procedure and with
clinical problems sufficient to justify invasive investigation, and to those institutions with the facilities and trained staff sufficient to pursue the investigation.

_**Left ventricular angiography**_ is performed routinely whenever coronary angiography is undertaken for the assessment of ischaemic heart disease. It is also undertaken to assess mitral incompetence when mitral valve replacement is thought necessary and for the assessment of left ventricular morphology and performance in primary diseases of the left ventricle (e.g. congestive cardiomyopathy and hypertrophic cardiomyopathy) and in certain types of congenital heart disease. In addition to the drawback of requiring an invasive approach the technique also has the drawback that the rapid injection of a large volume (typically 40 ml) of contrast material over

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**Fig. 1.** X-ray. (a) Generalised cardiomegaly. The patient has a congestive cardiomyopathy. It is not possible to reach reliable conclusions on the size of the individual cardiac chambers or to be sure how much (if any) pericardial fluid is present. (b) Pulmonary venous hypertension and left atrial dilatation. The patient has mitral stenosis. The left atrium is dilated, the pulmonary venous markings are accentuated and there is upper lobe blood diversion. (c) Pulmonary arterial hypertension. The patient has primary pulmonary hypertension. The main pulmonary artery is enlarged, the proximal pulmonary artery markings are accentuated and there is 'pruning' of the peripheral pulmonary markings. (d) Left ventricular aneurysm. Close-up of apical region of the heart from a penetrated PA chest film. An oval aneurysm, delineated by a fine ring of calcification, is seen in the region of the left ventricle. The patient had an old, extensive anterolateral infarction.
approximately three seconds can itself change left ventricular function[2]. Nevertheless, this is the technique against which others must be judged.

The simplest images to consider are those of the opacified left ventricular cavity at end-systole and end-diastole. These provide information from which estimates of end-diastolic (EDV) and of end-systolic (ESV) ventricular volumes can be determined[3]. Stroke volume (SV) is then given by the relationship SV = EDV - ESV and ejection fraction (EF) from the relationship EF = SV/EDV. In the adult the normal EDV is 70 ± 20 ml/m², the normal SV is 45 ± 13 ml/m² and the ejection fraction 0.67 ± 0.08[4]. Examples of the use of end-systolic and end-diastolic frames from left ventricular cine-angiograms in the evaluation of left ventricular function are shown in Figs 2 and 3.

There are drawbacks in attempting to evaluate left ventricular function using only end-systolic and end-diastolic frames, for this technique gives no impression of the rate of left ventricular fibre shortening or of the synchronicity (or lack of it) of shortening of the left ventricular fibres. In the context of the normal clinical appraisal of left ventricular angiograms, the rate and degree of co-ordination of left ventricular timing are sensed (admittedly, very subjectively) by the cardiologist when evaluating the projected left ventricular cine-angiogram. More formal (and less subjective) evaluation of these features needs a great deal of care, and some form of objective analysis is desirable[3].

Coronary angiography is an obligatory investigation whenever coronary artery surgery is contemplated and is very highly desirable (some would say essential) whenever valve replacement is being considered or any form of open heart surgery is to be undertaken on an adult. The enthusiastic (otherwise known as ‘aggressive’) cardiologist also recommends coronary angiography for inappropriately young patients with ischaemic heart disease and, less frequently, for other special indications (Table 1). It should be noted that definition of the term ‘inappropriately young’ has been avoided.

The fact that a risk to the patient is involved in coronary angiography is widely appreciated. What is less well known is the extent of that risk and the relative risks involved in alternative investigation by exercise electrocardiography or in not investigating the patient at all. Multi-centre studies involving more than 25,000 patients have shown a mortality rate of the order of 0.1 per cent for coronary angiography. The rate of myocardial infarction induced by the procedure is between 0.1 and 0.2 per cent and of cerebral embolism is 0.08 per cent[5]. These figures represent the combined experience of numerous centres, some with much smaller workloads than others. In the hands of an experienced investigator and in a laboratory with a continuously high work rate, the risks are likely to be substantially less. Furthermore, in the ten years which have elapsed since these data were collected techniques have improved and risks fallen further. Even at the quoted level, however, the mortality rate is only 10 times that for the graded exercise stress test (GXT) (mortality rate 0.01 per cent, n = 170,000[6]) and is also only 10 times the average daily mortality rate for patients with angina (average annual mortality = 4 per cent[7]). In comparing the risks of coronary angiography with the GXT, two important features should be noted. The first is the reliability and detail of the information provided by the coronary angiogram compared with that provided by the GXT and the second is the nature of the population undergoing the test. The majority of patients undergoing coronary angiography have significant coronary artery disease. A highly significant number of those involved in the multi-centre GXT evaluation had no detectable coronary disease.

Clearly the (small) risks of coronary angiography do
Fig. 3. Abnormal left ventricular contrast angiogram (right anterior oblique view). (a) End-diastolic frame. The catheter ascends the aorta from the right femoral artery. It has passed through the aortic valve and the distal loop is seen (arrowed) in the left ventricular cavity. (Courtesy Pitman Medical[1].) (b) End-systolic frame. All parts of the ventricular wall have contracted substantially and the end-systolic volume is very small. The apical part of the left ventricular cavity is obliterated and the catheter loop is seen without any surrounding contrast agent. (The ejection fraction is very high.) A small whiff of mitral regurgitation is seen (MR) and there is narrowing of the left ventricular outflow tract (interrupted arrow) formed by the interventricular septum (S) and by the anterior mitral leaflet (AML).

The appearances are those of hypertrophic cardiomyopathy. (Courtesy Pitman Medical [1].)

Table 1. Indications for coronary angiography.

| UNIVERSALLY AGREED                              |
|------------------------------------------------|
| 1. Prior to coronary artery surgery            |
| 2. Adults requiring open heart surgery         |

| ENTHUSIAST’S INDICATIONS                      |
|-----------------------------------------------|
| Common                                        |
| 1. Inappropriately young patients who have sustained myocardial infarction |
| 2. Inappropriately young patients who have developed angina pectoris       |
| 3. Young patients with symptoms which raise the possibility of coronary artery disease |

| Infrequent                                    |
|------------------------------------------------|
| 1. Young patients with ECG findings suggesting possible coronary disease |
| 2. Abnormal ECG findings which threaten the patient’s livelihood unless coronary disease can be excluded. |
| 3. Anxious subjects with a strong family history of ischaemic heart disease |

Examples of frames from coronary angiograms are shown in Fig. 4.

Nuclear Techniques

Nuclear investigative techniques involve very low invasiveness and little discomfort or inconvenience to the patient. However, there are limitations inherent in the resolving power of nuclear techniques, which, in general, do not reliably demonstrate tissues less than 1 cc in volume. Nevertheless, current techniques can, in appropriate circumstances, demonstrate the extent and distribution of viable myocardium, localised areas of ischaemia induced by exercise or by drugs, recent myocardial cell damage and global and regional left ventricular function. Infarcts involving less than 3 to 7 g of myocardium are unlikely to be shown and edge detection by nuclear ventricular angiograms is considerably more difficult than with contrast angiography. Nuclear techniques thus currently provide a complement to, rather than a substitute for, electrocardiography, plain chest radiography and cardiac catheterisation.

Nuclear Imaging in the Diagnosis of Myocardial Infarction.

Two general approaches have been used for the detection of recent myocardial ischaemia or infarction. The first, known as infarct-avid imaging (also known as positive imaging and ‘hot-spot’ scanning), demonstrates recent myocardial damage using radio-pharmaceuticals that concentrate selectively in acutely injured cells. The second, known as ionic tracer scanning (or negative imaging or ‘cold-spot’ scanning), uses ionic tracers which behave in a fashion similar to the potassium ion and accumulate in viable, perfused myocardium.

The most commonly used agent for hot-spot scanning is $^{99m}$Tc-mannous pyrophosphate. This agent is taken up by normal bone and is the radio-pharmaceutical of choice for bone scanning. It is also taken up by freshly injured myocardium, and a positive myocardial scan is likely to

not need to be stressed to the patient for whom the investigation is essential but should be pointed out to those for whom it is not obligatory (Table 1).

The findings at coronary angiography have been shown in several studies to have prognostic significance[8,9]. When the data from several centres are combined, it appears that the annual mortality rate, if only one of the three major coronary arteries (anterior descending, circumflex, right) has a 50 per cent or greater stenosis, is 2 per cent. With two-vessel disease the rate is 7 per cent, with three-vessel disease it is 11 per cent and with left main stem stenosis it is 20 per cent[10]. The average annual mortality for patients with angina is 4 per cent for those without previous infarction and 5 per cent for those with prior infarction[7].
Fig. 4. Single frames from coronary angiograms. (a) Normal right coronary artery, right anterior oblique view. (b) Extensively diseased right coronary artery, right anterior oblique view. The major branches are identified. (c) Normal left coronary artery, right anterior oblique view. (d) Extensively diseased left coronary artery, right anterior oblique view. There is almost complete occlusion of the main stem. The circumflex system is extensively diseased and filling is only seen for a short length. There is a 50 per cent narrowing in the proximal part of the anterior descending artery. (e) Complete occlusion of the main stem of the left coronary artery, left anterior oblique view. Only a small number of such cases are reported in the world literature. Fig. 4(b) shows a frame from the right coronary angiogram in the same patient. He had severe angina. The resting electrocardiogram showed T wave inversion in lead I and aVL but was otherwise within normal limits. (f) Severely diseased left coronary artery, right anterior oblique view. The anterior descending artery is completely blocked at its origin and the circumflex system is severely diseased.
be demonstrable when at least 3 g of acutely necrotic myocardium are present, provided that there is persistent residual collateral coronary blood flow in the area of myocardial damage (of the order of 20–40 per cent of the normal flow) and provided the time interval between the clinical onset of infarction and the scanning procedure is between 24 and 96 hours. An example of a normal and an abnormal pyrophosphate scan is shown in Fig. 5. Studies from many centres have shown a false positive rate of about 17 per cent and a false negative rate of about 6 per cent[11]. The recorded causes of false positive pyrophosphate scans include unstable angina, left ventricular aneurysms, cardiomyopathy, valvular calcification, myocardial contusion, residual isotope within the blood pool of the cardiac cavities, rib fractures, breast tumours, calcified costal cartilages, skeletal muscle damage and cardioversion.

The agent most commonly used for cold-spot scanning is 201thallium, which is taken up by healthy myocardium. Its uptake is dependent upon perfusion of the myocardium, the viability of the myocardial cells and the integrity of the myocardial cell membrane. Defects in the normal distribution of thallium may thus indicate infarction or ischaemia. In general it has been shown that defects in scans obtained with the patient at rest indicate infarction and that defects found on scanning during exercise but not at rest indicate local myocardial ischaemia. In the normal thallium scan the left ventricle is shown as a doughnut-shaped outline, with an area of lesser activity in the centre of the scan indicating the left ventricular cavity. The scan is usually viewed in the anterior, left anterior oblique and left lateral projections and in these projections the major zones of the left ventricle can be recognised (Fig. 6). Figure 7 shows an example of a thallium scan indicating a zone of ischaemic myocardium. The left-hand column shows the appearances in three views taken within minutes of the completion of exercise.

**Fig. 5.** 99mTc-stannous pyrophosphate scans. The left-hand column shows a normal scan in the anterior (AP), left anterior oblique (LAO) and left lateral (LL) views. The upper and lower limits of the sternum are indicated in the AP and LAO view by the short arrows. Normal uptake in the obliquely running ribs can be seen to the left (patient’s left) of the sternum in the AP and LAO views. The right-hand column shows an abnormal scan. The sternum is recognisable (short arrows). There is dense uptake of the tracer in the acutely infarcted myocardium (chunky arrows). (Courtesy Oxford University Press[11].)

**Fig. 6.** Normal 201thallium scan. Normal distribution of activity is seen, predominantly in the myocardium of the left ventricle. Decreased activity in the area of the cavity of the left ventricle is recognisable in the anterior and LAO 45° view. The use of three views permits visualisation of different regions of the left ventricle. (Courtesy Pitman Medical[1].)

**Fig. 7.** 201Thallium myocardial perfusion study at exercise and after periods of rest to permit redistribution. A large apical defect in uptake is seen in all views at exercise (arrow); during the next few hours redistribution occurs and the defect virtually disappears. (Courtesy Churchill Livingstone [12].)
The thallium was administered intravenously immediately prior to the completion of exercise. A major defect is apparent in the infero-apical wall. Further scans taken after allowing one and a half and five hours for the redistribution of thallium have shown normalisation of the appearances, indicating that the initial defect was due to ischaemia and not to infarction. By contrast Fig. 8 shows a defect present at the end of exercise, which was unchanged after six hours. A sustained defect of this type indicates non-viable myocardium. The demonstration of a defect (either infarction or ischaemia) on thallium scanning depends upon the presence of at least 7 g of abnormal myocardium. It is claimed that no false negative scans occur if the investigation is undertaken within six hours of the onset of symptoms but that is not a reasonable proposition for most working environments. Considerable skill is involved in the interpretation of a thallium scan and the over-enthusiastic use of this procedure is very much to be discouraged. It does not provide a very reliable screening test for ischaemic heart disease but it can be very useful when a localised area of exercise-induced ischaemia is seen to correlate with an angiographically demonstrated stenotic lesion of uncertain significance.

Scintigraphic Determination of Left Ventricular Function. Numerous radio-pharmaceuticals can be used for the scintigraphic determination of left ventricular function. The properties common to all such pharmaceuticals are that they should remain in the intravascular compartment for a significant period of time and that they should be easily detectable by modern nuclear imaging devices. The most commonly used agent is the patient’s own red blood cells labelled with \(^{99}\)Tc\(^m\). Two basic techniques are available, the first-pass technique and the equilibrium technique.

In the first-pass technique, the first passage of the radioactive bolus through the central circulation is studied. Sequential images follow the passage of the tracer through the central circulation (Fig. 9). Using computer processing techniques, both the left ventricular ejection fraction and also estimates of regional left ventricular wall motion may be determined.

The equilibrium technique is also referred to as gated cardiac blood pool imaging or as multi-gated acquisition (MUGA) imaging. The radioactive tracer is allowed to mix completely with the circulating blood volume. Again, the most commonly used tracer is the patient’s own red blood cells labelled with \(^{99}\)Tc\(^m\). Since the left and right ventricular cavities are both shown with the tracer at equilibrium, the left ventricle can only be studied in a view in which its image is physically discreet from that of the right ventricle. In practice this means a modified left anterior oblique projection, and an example of end-systolic and end-diastolic frames from such a study is shown in Fig. 10.

The first-pass and equilibrium techniques each have their own advantages and drawbacks. The first-pass technique is briefer; this is important if the patient cannot lie still or if the cardiac rate or rhythm is liable to change. This technique allows the left ventricular nuclear angiogram to be viewed in any chosen projection. However, in the equilibrium procedure the injection technique is not
critical and the procedure allows sequential measurements of global left ventricular function to be obtained after a single tracer injection. Both techniques provide reasonably reliable estimates of left ventricular ejection fraction but neither technique can be currently said to provide entirely reliable estimates of regional left ventricular wall motion.

Echocardiography

Echocardiography has an established place as an imaging technique providing information on the structure and function of the diseased and of the normal heart. As now practised there are two separate techniques which require different equipment and different recording methods. Each technique has its advantages and limitations.

M-mode Echocardiography. The single transducer system is mainly used in the M-mode[1] where it has a well-established role in cardiac investigation. It has a resolution of 1 mm and thus provides precision imaging. Its major limitations are that it only provides measurements along a single axis at a time, that it can only provide measurements in a restricted zone within the heart and that, even within this zone, it can only provide measurements in a proportion of patients. Factors making it more likely that a technically satisfactory recording will be unobtainable include obesity, lung disease and increasing age.

A normal M-mode scan of the heart is shown in Fig. 11. M-mode echocardiography has proved extremely helpful in the assessment of various conditions (Table 2).

Mitral Valve Disease. The normal pattern of movement of the mitral valve in diastole is an ‘M’ shaped motion, the upward initial movement representing initial maximal

Fig. 10. Gated equilibrium studies of left ventricular function, LAO 45 view. The upper two images show end-diastolic (ED) and end-systolic (ES) frames. In the lower part of the illustration the same two images are repeated with the computer-determined left ventricular margins superimposed. The arrows indicate the position of the interventricular septum. (Courtesy Pitman Medical[1].)

Fig. 11. Normal M-mode scan. (a) The directions of transmission of the ultrasound beam in an M-mode scan. The ‘section’ through the heart passes through the apex and through the aortic area. The plane of this section is not horizontal but runs from inferiorly and to the left to superiorly and to the right. (b) Normal M-mode scan obtained from scanning in directions shown in (a). The recordings corresponding to position 1, 2 and 3 are shown. (Courtesy Pitman Medical[1].) (c) Normal M-mode scan to show the thickness of the left ventricular free wall and of the interventricular septum. (Courtesy Pitman Medical[1].)
opening and the first downward movement (EF slope or mitral closing velocity) representing the normal partial mitral valve closure in mid-diastole. The normal range of the EF slope in adults is from 80–200 mm/sec. A reduction in this velocity is consistently found in mitral stenosis, although reduction may also occur in conditions associated with reduced left ventricular compliance (e.g., aortic stenosis, hypertrophic cardiomyopathy and hypertension)[1]. When EF slope reduction is caused by mitral stenosis the smaller, posterior leaflet is dragged forwards with the anterior leaflet in diastole. Mitral incompetence cannot be reliably detected directly from the echocardiogram although its presence can sometimes be inferred from the high amplitude of movement of the leaflets and the associated left atrial and left ventricular dilatation.

Posterior movement of the mitral leaflets during systole is a reliable sign of mitral valve prolapse, and systolic anterior motion of the mitral valve leaflets is frequently found in hypertrophic cardiomyopathy.

The echocardiogram is a more sensitive detector of valvar calcification or fibrosis than is fluoroscopy[1].

**Left Ventricular Function.** M-mode echocardiography provides a highly accurate and reproducible assessment of a single dimension within the left ventricle. Provided that the function of the left ventricular myocardium is uniform and the left ventricular shape is normal, estimates of ventricular volume at end-systole and end-diastole (and therefore of stroke volume) may be made. However, in the presence of ventricular dilatation, the ventricular shape is less ellipsoidal and more spherical, and extrapolation from a reliable measurement of a single ventricular dimension to calculations of ventricular volume become unjustifiable[13]. In addition to providing accurate measurements of one dimension of the left ventricular cavity, echocardiography provides an accurate measurement of the interventricular septal thickness and of the left ventricular free wall thickness (Fig. 11 (c)). (These thicknesses are, of course, representative only of one small zone of the ventricular wall in each case.)

**Pericardial Effusion.** Pericardial effusion is demonstrable by echocardiography with a high degree of reliability, although false positives and false negatives can occur. False positives can be avoided if care is taken to ensure that the anterior wall of the heart, the posterior wall and the interventricular septum are all clearly seen (Fig. 12).

**Table 2.** Conditions for which M-mode echocardiography is a suitable investigation.

| Condition                                                                 |
|---------------------------------------------------------------------------|
| Mitral valve disease (especially mitral stenosis and mitral valve prolapse) |
| Left ventricular function (where the function is uniform throughout the ventricle) |
| Pericardial effusion                                                       |
| Intracardiac myxoma                                                       |
| Hypertrophic cardiomyopathy                                               |
| Atrial septal defect                                                      |
| Tricuspid stenosis                                                        |

Echocardiographic estimates of the volume of fluid in the pericardium are only crude approximations.

**Intracardiac Myxoma.** This condition provides a dramatic example of the diagnostic power of echocardiography but false positive and false negative results may occur. Echoes simulating those of a myxoma may be seen if excessive gain is used on the equipment or in the presence of flail mitral valve leaflets. False negative findings may occur if the gain is too low and, of course, the echocardiogram will fail to detect a myxoma if it is not possible to obtain readings of high technical calibre. An example of the
echocardiographic findings in the presence of a large atrial myxoma is shown in Fig. 13.

**Hypertrophic Cardiomyopathy.** This condition is diagnosable by echocardiography in the majority of cases, provided recordings of high technical calibre can be obtained. Diagnostic features include an abnormally thick interventricular septum (ratio of thickness of interventricular septum to that of left ventricular free wall of 1.3 or more[14]) and, when there is outflow tract obstruction in addition to the hypertrophy, there is systolic anterior movement of the mitral leaflets[15]. An example is shown in Fig. 14.

**Fig. 14. M-echocardiogram showing hypertrophic obstructive cardiomyopathy.** (a) The interventricular septum is abnormally thick, septal movement is appreciably less than that of the left ventricular free wall and there is systolic anterior movement of both mitral valve leaflets. The systolic anterior movement (SAM) is more clearly seen in (b). (Courtesy Pitman Medical[1].)

**Other Conditions.** Echocardiography can be used to demonstrate tricuspid stenosis, pulmonary stenosis (a difficult demonstration) and vegetations on valves in the presence of infective endocarditis. Atrial septal defect cannot be visualised directly by M-mode echocardiography but is demonstrable by virtue of the changes which it induces in right ventricular size and in the movement of the interventricular septum. The right ventricle is often larger than usual and there is paradoxical movement of the interventricular septum.

**Cross-sectional Echocardiography**

The alternative echocardiographic technique requires equipment which is between five and 10 times as expensive as that required for M-mode echocardiography. Numerous terms have been used to describe this technique, including cross-sectional echocardiography, two dimensional echocardiography and real time echocardiography. The principle of the technique is the simultaneous production of a number of individual lines of B-mode echo recordings on the oscilloscope screen. Each line shows an individual cross-section similar to that used in the M-mode display but without the application of a time-based 'sweep' to the oscilloscope trace. Each line therefore remains in the same location on the oscilloscope. (The 'M' in the M-mode refers to movement as the echo pattern is made to sweep across the oscilloscope. The 'B' in B-mode refers to brightness, for the returning echoes are modulated to relate the brightness to the amplitude of the returned echo.) When the numerous individual lines are viewed together they produce an image of a cross-section of the heart, movement of the cardiac structures with function being apparent (Fig. 15). The images are reproduced about 30 times per second to give a dynamic scan. One B-mode scan is produced at a time. There are about 30 individual transducers arranged within the single transducer holder and rapid electronic switching...
among the transducers is employed in the system known as ‘phased array’. In some systems a sector of 90° may be achieved.

Cross-sectional echocardiography has proved to be immensely valuable in the diagnosis of congenital heart disease and it is in this area that the technique has made its greatest impact. Infants and neonates are relatively easy to examine by this technique (provided they have been fed and are not restless). The vast majority of congenital cardiac abnormalities are demonstrable and to some degree quantifiable by this technique but both the recording and the interpretation require experienced observers. Cross-sectional echocardiography is unlikely to become widely used in evaluation of ischaemic heart disease in the near future partly because of the great expense involved in purchasing the equipment but mainly because of the shortage of experienced investigators. In the foreseeable future it seems likely that its use in this area will remain confined to specialised cardiac centres.

Examples of the use of cross-sectional echocardiography in the diagnosis of congenital heart disease are shown in Figs 16 and 17.

Other Echocardiographic Techniques

A special echocardiographic technique uses a pulsed Doppler system to produce information on the direction and velocity of blood flow; its role is uncertain at present.

‘Contrast’ echocardiographic visualisation of the cardiac cavities after the injection of ‘echogenic’ substances may be used to demonstrate shunts. The way in which these substances (which include normal saline, dextrose and indocyanine green) produce their effects is controversial. The presence of multiple minute air bubbles, turbulence, cavitation and varying acoustic impedances have all been held responsible.

A new development is the use of amplitude tissue characterisation using enhancement techniques and colour displays. These techniques offer the hope of demonstrating features such as endocardial fibrosis, myocardial ischaemia and myocardial infarction. It is likely that significant developments will occur in this area within the next few years.

One or two centres are working on the possibility of constructing three-dimensional images of the heart but for the next decade such techniques are unlikely to be of more than research interest.

Techniques undergoing Evaluation

Computed Tomography (CT)

The fundamental scientific concepts on which computed tomography is based were described in 1964[16] but the first usable scanner was not reported until 1973[17]. The
technique has found extensive application first in brain scanning and subsequently in whole body scanning. The heart, however, presents a particularly great challenge, principally because of the amount of movement of the various cardiac structures which takes place during the scanning time. The application of this technique is limited now by the lack of time resolution and of simultaneous multi-section capability, defects likely to be rectified in the near future.

Currently a typical scan takes approximately 2.5 seconds and the scanning procedure can be repeated about every 3 seconds. Electrocardiographic gating can permit controlled accumulation of data from specific phases of the cardiac cycle. The integrated data can then be used to reconstruct an image of the desired phase of the cardiac cycle. When gating techniques are not used the dynamic flow of contrast to the heart can be studied and useful information acquired in this way.

The use of gating techniques is in its infancy and single-scan imaging of the heart after the intravenous injection of contrast has proved surprisingly successful despite the inevitable motion artefacts which occur within the 2.4 second scan time. Such a scan, which includes several heart beats, produces an integrated systolic-diastolic image of the heart and contains a great deal of diagnostic information. The integrated scan is usually closer to a diastolic than to a systolic study if the heart rate is below 90, because of the relatively greater duration of diastole at such rates.

Large-scale study of the areas of usefulness and of the reliability of CT in cardiac investigation are not yet available but some examples of use are shown in Figs 18-23.

Digital Subtraction Angiography (DSA)

This technique is increasingly used in the recognition and assessment of stenotic lesions of major central arteries. The technique is being developed in the area of left ventricular angiography. As discussed earlier, left ventricular angiography with direct intraventricular injection of contrast medium (a typical volume being 40 ml) is the accepted standard for the analysis of left ventricular shape and volume and for the estimation of left ventricular ejection fraction and regional wall motion. Peripheral venous injection of the contrast agent, using conventional X-ray equipment, does not produce images of the left ventricle that are adequate for diagnostic purposes because of the low contrast between the myocardium and the diluted radio-opaque material within the ventricular cavity and because of interference produced by the overlap of adjacent cardiac and extra-cardiac structures. Digital angiography makes possible the acquisition of adequate ventricular contrast studies from either the
peripheral injection of 30-40 ml of contrast agent or from the direct intraventricular injection of 10 ml of contrast. The former approach eliminates the drawback of invasive investigation and the latter makes it less likely that the analysis would be disturbed by ventricular arrhythmias and permits more studies of left ventricular performance than would otherwise be possible. The most commonly used method of processing the image is called mask mode subtraction. An initial pulsed X-ray exposure is obtained, digitised and stored as a mask. Contrast medium is subsequently injected and each frame of a fluroscopic image is stored digitally. Each frame is subtracted, pixel by pixel, from the stored mask and the subtracted digital image is converted back to analogue format and displayed. The mask subtraction helps eliminate soft tissue or bone shadows and enhances visualisation of the ventricular cavity. The movement of the heart presents problems which do not so obviously arise in digital subtraction angiography of more static structures, such as the major arteries in the neck. Nevertheless, adequate ventricular visualisation can be achieved by this technique (Fig. 24).

The rapid further evaluation of this technique is to be expected and the major hope for the future is that it may prove possible to obtain coronary angiograms (from peripheral venous injection) of sufficient quality to serve as a screening procedure; but it is unlikely that the quality

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**Fig. 18.** Computed tomographic cuts at the level of (a) the right ventricular outflow tract and (b) the aorta below the aortic arch showing dissection of the descending thoracic aorta.

**Fig. 19.** Computed tomographic (CT) images in the heart in ischaemic heart disease, (a) Section at mid-ventricular level in diastole. Note the thinning of the anterior left ventricular wall at the site of an infarct. (b) Section from same patient and at same level as (a) but in systole. Note the absence of movement of the ventricular wall at the same site as the thinning.

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occupying effects of lack

Fig. 20. CT section through the ventricles and atria. Note the lack of contrast in the left atrium as a result of the space-occupying effects of a large left atrial myxoma.

will be sufficient for pre-surgical assessment in the foreseeable future.

Nuclear Magnetic Resonance (NMR)

The property upon which NMR is based was discovered in 1956 and has been extensively used in chemical spectroscopy since that time. In 1971 it was discovered that neoplastic tissues have magnetic relaxation times different from those of normal tissue and in the late 1970s the techniques of producing NMR images of potentially diagnostic quality were developed. The technique is still very much in its infancy and the potential role of NMR in cardiac imaging is not yet clear.

Fig. 21. CT section to show native coronary vessels (circumflex and left anterior descending (LAD)) and coronary saphenous bypass grafts.

Biological tissues contain high concentrations of hydrogen, which is a paramagnetic substance. The effect of applying a strong magnetic field to hydrogen nuclei (protons) that are randomly orientated in normal tissue is to induce the protons to lie along lines of magnetic force. If gradients of field strength are induced within the magnetic field, populations of hydrogen ions can be spatially separated from their neighbours. Variations in the concentration of hydrogen ions within the plane of a given magnetic field strength give rise to variations in the magnetic signal that can be detected and such variations form the basis on which the imaging of organic structures by this technique depends.

Many problems remain to be solved before clinically useful NMR images of the heart are obtained and the technique is likely to remain costly, but the potential appears to be considerable. The technique offers the prospect of providing metabolic information as well as structural information and one of the major advantages is that so far it has not been shown to have any adverse effects. Patients with metal prostheses or pacemakers must be excluded and pregnant patients should be excluded until more long-term information on possible adverse effects is available.

Examples of early NMR images of the heart are shown in Fig. 25.

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Fig. 22. CT section at mid-ventricular level from a patient with extensive infarction and a thrombus in the left ventricular cavity.
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