Jubilee Editorial

Cardiac imaging 50 years on

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When the Cardiac Club became the British Cardiac Society 50 years ago radiological examination was the only means of imaging the heart; however, the physical basis of many of the newer forms of imaging was already established. Roentgen's exciting discovery of 1895 stimulated Williams to report on *x* ray examination of the heart the following year. He noted that "the pulsations of the heart may be followed with the fluoroscope, not only ventricular, but also auricular contractions and dilatations" and he went on to comment that the first medical case he examined was that of a man with an enlarged heart (seven inches in transverse diameter).¹ That he managed to image the heart, although the man was wearing two shirts and a waistcoat, speaks more for his skill than the sartorial style of his subject. Roentgenology of the skeleton and chest rapidly progressed, although xenophobia during the first world war changed the name of the discipline to radiology. Radiological examination of the heart was slow to spread, however, and as late as 1920 Sir James MacKenzie wrote "Indeed I am doubtful if an *x*-ray examination of the heart has ever thrown the slightest light on any cardiac condition".²

But radiology did flourish and by 1933 John Parkinson and Crichton Bramwell, both members of the Cardiac Club, had, with Peter Kerley, written three important consecutive papers on cardiac radiology in the *British Medical Journal*.³⁻⁵ By 1937 the British Association of Radiologists had been formed and in November of that year its first fellowship examinations were held.⁶ There may still have been controversy about whether an *x* ray picture was a radiograph or a radiogram⁷ but radiology of the heart was well established. In 1937 Roesler published his book *Clinical Roentgenology of the Cardio-*

vascular System,⁸ and in 1939 the first volume of the *British Heart Journal* contained a detailed radiological account of the volumetric reconstruction of the heart in health and disease by Spillane who wrote that "Radiological study of the heart has now become a well recognised and valuable procedure in the investigation of a cardiac patient".⁹

Early imaging techniques

Much of radiological investigation was done by fluoroscopy, and the red goggles used as an aid to dark adaptation became part of the practising cardiologist's uniform. Despite the risk of considerable exposure to radiation the practice of fluoroscopic examination of the heart persisted until the 1960s.¹⁰ The size and shape of the heart were recorded on a chest film by a process sometimes referred to as teloradiography because the patient and film were positioned 300 cm from the tube, a distance much greater than used for fluoroscopy. The motion of the heart in systole and diastole could be illustrated by kymography. *X* rays were passed through the chest to a film which moved at a uniform rate behind a grid of lead strips.

In 1937 angiography was in its infancy. Forssmann had already recognised the potential of his method of catheterisation for demonstrating the anatomy of the heart and great vessels. In 1931 he used contrast material to visualise the heart chambers in a dog.¹¹ In the same year Moniz, de Carvalho, and Lima of Lisbon injected sodium iodide into the superior vena cava or the right atrium to produce images of the pulmonary circulation in man.¹² Late in 1937 Castellanos, Pereiras, and Garcia, the Cuban pioneers, reported the use of contrast angiocardiology in the diagnosis of congenital heart disease.^{13 14} The subsequent rapid progress in cardiac angiography owes much to these and other pio-

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neers but also to developments in fluoroscopy and in contrast agents. Thorotrast (thorium dioxide) was an early popular contrast agent but by 1937 the potential hazards of its radioactivity were recognised⁸ and diotrast then became the most widely used agent for angiography. The safety of modern contrast agents of low osmolality was still a long way off.¹⁵

In 1945 Radner reported on his attempt to visualise the coronary arteries by inserting a 1.5 mm needle through the manubrium sterni into the ascending aorta and injecting contrast material (thorotrast).¹⁶ After this report demonstration of the coronary arteries was attempted by various techniques but it was not until selective catheterisation was developed by Sones *et al*¹⁷ and the modified transfemoral approach was introduced by Judkins with thermoplastic preformed catheters that coronary arteriography became an established technique.¹⁸

Analysis of images

The nineteenth century mathematician Charles Babbage is often credited with early attempts to devise a computer; none the less digital computers did not become available till the late 1950s. The transistor was introduced to the commercial world in the early 1960s and the resulting progress in digital computing was so rapid that today it is difficult to conceive of imaging without the ubiquitous computer. Subtraction imaging, based on the difference between a mask image and the contrast image, had been used intermittently in radiology but once the image could be digitised subtraction angiography became comparatively easy. Subtraction angiography has been used to detect regional ventricular dysfunction at rest and during exercise.¹⁹ Initially, it was thought that this technique might avoid selective catheterisation; this has been achieved in only a limited number of applications, such as carotid angiography,²⁰ but subtraction angiography can be used to produce images with high definition, and its full potential in angiography has not yet been realised. Digital radiology may also produce a further revolution in our ability to store and retrieve radiographs so that the "missing x ray" may be a thing of the past.

Another outgrowth of digital technology was the development of computed tomography. When Ambrose and Hounsfield first demonstrated the technique²¹ it was clear that there was to be a revolution in neuroradiology. The very long scan times meant that their technique could not be readily applied to the heart, and even the newer machines with a scan time of 2–5 seconds limited its use in

cardiology. Heat load limitations and the angular momentum of rotating x ray tubes made it necessary to adopt an alternative strategy. The x ray beam has been replaced with a magnetically reflected electron beam so the ultimate scan speed is limited only by the need to obtain sufficient photons in a short time. Exposure times of 50 ms are now possible and computed tomographic cineangiography has been used in a number of centres to demonstrate detailed cardiac anatomy. Myocardial perfusion can be assessed by examining thin slices of myocardium and noting the changes in density of injected contrast agent. Computed tomographic cineangiography appears to be useful in demonstrating graft patency.²²

Ultrasonography and Doppler

The rapid developments in electronics and computing stimulated the use of other physical phenomena to image the heart. Jacques and Pierre Curie described the production of very high frequency sound waves from piezoelectric crystals in 1880²³ and by the mid 1930s ultrasound was being applied to detect flaws in metals. The technique of sonar (sound navigation and ranging), conceived after the sinking of the Titanic and originally developed in the first world war, was important in the detection of submarines in the second world war. Ultrasound was first used medically in an attempt to locate brain tumours.²⁴ In Britain Donald pioneered the use of ultrasound in obstetrics and gynaecology²⁵ and shortly afterwards the technique began to be used for investigation of heart disease. Early work used ultrasound in the same way as x rays, collecting the signal once it had passed through the chest, but this was abandoned in favour of pulsed reflected ultrasound. Edler in Sweden did much to develop the method²⁶; he used it to recognise the abnormal motion of the anterior leaflet of the mitral valve in mitral stenosis. By the late 1960s M mode echocardiography was being used to identify valve function,²⁷ to detect pericardial effusions,²⁸ and to diagnose hypertrophic obstructive cardiomyopathy²⁹ and left atrial myxoma.³⁰ Subsequent developments in real time and Doppler echocardiography have made ultrasound the first diagnostic procedure in the investigation of a wide range of cardiac conditions. Fetal ultrasound investigation can detect congenital heart disease in utero³¹—a long step forward from the pioneering angiograms of Castellanos and coworkers.^{13 14}

Radionuclide imaging

In 1937 few clinicians would have contemplated

using radionuclides in cardiovascular investigation, but 10 years before Blumgart and Weiss had described the injection of radium C salt into an arm vein; they timed the arrival of the radioactivity in the artery of the opposite arm by the response of a Wilson cloud chamber.³² Radionuclide imaging of the cardiovascular system had to await the development of improved imaging devices. Rejali and colleagues used a rectilinear scanner to investigate blood pools of the thorax and abdomen.³³ The introduction of the large crystal scintillation camera³⁴ and technetium-99m labelled tracers made it possible to view the passage of a tracer bolus through the central venous and arterial circulations in a series of camera images.³⁵ The development of image processing with computers and the concept of cardiac gating led to the development of techniques for estimation of cardiac output and left ventricular ejection fraction. Techniques have been developed to quantify valve regurgitation and estimate left to right or right to left shunting, and further processing of ventricular images has produced a whole series of function images designed to assist in interpretation of regional abnormalities. Kety used radioactive sodium to determine blood flow in the myocardium.³⁶ Others have injected diffusible tracers such as xenon-133 or krypton-85 into the coronary artery or into the heart muscle itself and have used the disappearance or wash out of radioactivity as an index of tissue blood flow.

Cannon *et al* used a multicrystal scintillation camera to derive myocardial blood flow from regions corresponding to each of the camera crystals.³⁷ The suitability of a series of intracellular cation analogues of potassium for identifying perfused myocardium was investigated. Potassium-43 had some success but this was replaced by thallium-201, which is now widely used by many groups, particularly to demonstrate areas of transient ischaemia after exercise. There are still limitations to thallium myocardial scintigraphy and newer technetium labelled compounds are being examined and show some promise.³⁸ The development of positron emission tomography using carbon-11, oxygen-15, nitrogen-13, or fluorine-18 allows imaging of myocardial metabolism, and this technique promises to be useful for the investigation of regional abnormalities in perfusion and metabolism.³⁹ Positron emission tomography gives a very precise spatial resolution and it has encouraged the development of three dimensional reconstruction techniques for gamma emitting isotopes. This development of single photon emission computed tomography is a cheaper option than positron emission tomography and is more likely to be used in the investigation of cardiovascular disease in the near future.

Magnetic resonance imaging

Founding members of the British Cardiac Society are unlikely to have paid great attention to a paper published in 1936 by Gorter in which he reported his unsuccessful attempts to find resonance of lithium-7 nuclei in crystalline lithium fluoride.⁴⁰ And in 1946 members may have missed reports of the successful demonstration of nuclear magnetic resonance in letters to *Physical Review* by Purcell, Torrey, and Pound and by Bloch, Hansen, and Packard,^{41 42} but they will have noted the award of the 1952 Nobel prize for Physics to Bloch and Purcell. Nuclear magnetic resonance was used initially in chemistry and soon after it was applied to biochemistry. The metabolism of human muscle can be studied by nuclear magnetic resonance spectroscopy with phosphorus-31 and as the spatial resolution of the technique improves it should lead to an understanding of altered myocardial biochemistry in heart diseases.⁴³

In 1973 Lauterbur described the concept of imaging with nuclear magnetic resonance.⁴⁴ He recognised that the nuclear magnetic resonance spectrum was a one dimensional projection of nuclear density along the magnetic field gradient. By applying the gradient in a series of directions he was able to obtain two dimensional images using a mathematical back projection method similar to that used for computed tomographic x ray imaging. In 1977 Damadian and colleagues provided the first in vivo proton images of the human heart.⁴⁵ Like ultrasound, magnetic resonance imaging does not expose the patient to ionising radiation but in contrast with ultrasound the radio waves penetrate all the tissue including air and bone. Images can be made in any plane. Image quality has improved enormously in recent years and it is possible to demonstrate detailed anatomy and function by nuclear magnetic resonance.⁴⁶ The same techniques can be used to demonstrate blood flow^{47 48} and studies of anatomy and function are becoming a practical proposition. Another attraction of magnetic resonance imaging is its ability to document altered tissue constituents; also myocardial changes after infarction are clearly visible.⁴⁹ These changes were thought to be due to changes in tissue water but probably also reflect the process of cellular infiltration and repair.⁵⁰

Modern imaging now provides detailed knowledge of disordered anatomy and physiology in a manner that it was impossible to predict in 1937. Many of the methods are expensive, with some there is still considerable exposure to radiation of the patient and staff, and some are still at a very early stage of development. Today we must learn to use the available imaging techniques wisely. Tomorrow

we shall have to assimilate the best of the newer methods and discard the others. It would be foolish to predict the state of imaging in 2037. Which of today's methods will still be in use? Will imaging be based on a physical phenomenon yet to be explored?

References

- Williams FH. Notes on x-rays in medicine. *Trans Assoc Am Physicians* 1896;**x**:375-82.
- Mackenzie J. Chronic diseases of the heart. In: Christian HA, Mackenzie J, eds. *The Oxford medicine*. Oxford: Oxford University Press, 1920:387-492.
- Parkinson J. Radiology of heart disease. *Br Med J* 1933;**ii**:591-4.
- Kerley P. Radiology in heart disease. *Br Med J* 1933;**ii**:594-7.
- Bramwell C. Radiology in heart disease. *Br Med J* 1933;**ii**:597-9.
- Anonymous. Radiology and its relation to medicine. *Br Med J* 1937;**i**:564-5.
- Boulton Myles R. Radiograph or radiogram [Letter]. *Br Med J* 1937;**i**:530.
- Roesler H. *Clinical roentgenology of the cardiovascular system*. Springfield, Illinois: Charles C Thomas, 1937.
- Spillane JD. Volumetric reconstruction of the heart in health and in disease: a radiological study. *Br Heart J* 1939;**1**:333-44.
- Cooley RN, Schreiber MH. *Radiology of the heart and great vessels*. Baltimore: Williams and Wilkins, 1967.
- Forssmann W. Ueber Kontrast darstellung der Hohlen des lebenden rechten Herzens und der Lungenschlagader. *Munch med Wschr* 1931;**78**:489-92.
- Moniz E, de Carvalho L, Lima A. Angiopneumographie. *Presse Med* 1931;**39**:996-9.
- Castellanos A, Pereira R, Garcia A. La angiocardigraphia radio-opaca. *Archos Soc Estu clin Habana* 1937;**31**:523-96.
- de Los Reyes RP, Castellanos A, Pereira R. Angiography and its value. *Am Heart J* 1943;**25**:298-306.
- Hayward R, Dawson P. Contrast agents in angiocardiology. *Br Heart J* 1984;**52**:361-8.
- Radner S. Attempt at roentgenologic visualization of the coronary blood vessels in man. *Acta Radiol* 1945;**26**:497-502.
- Sones FM Jr, Shirley EK, Proudft WL, Westcott RN. Cine-coronary arteriography. *Circulation* 1959;**20**:773-4.
- Judkins MP. Selective coronary angiography. A percutaneous transfemoral technic. *Radiology* 1967;**89**:815-24.
- Detrano R, Yiannikas J, Simpfendorfer C, Hobbs RE, Salcedo EE. Exercise digital subtraction ventriculography for the detection of ischaemic wall motion abnormalities in patients without myocardial infarction. *Br Heart J* 1986;**56**:131-7.
- Seeger JF, Carmody RF. Digital subtraction angiography of the arteries of the head and neck. *Radiol Clin North Am* 1985;**23**:193-210.
- Ambrose J, Hounsfield G. Computerised transverse axial tomography. *Br J Radiol* 1973;**46**:148-9.
- Lipton MJ. Quantitation of cardiac function by cine-CT. *Radiol Clin North Am*. 1985;**23**:613-26.
- Curie J, Curie P. Sur l'électricité polaire dans les cristaux hémiedres à face inclinées. *CR Seances Acad Sci* 1880;**91**:383-9.
- Dussik KT. Über die Möglichkeit hochfrequente mechanische Schwingungen als diagnostisches Hilfsmittel zu verwenden. *Z ges Neurol Psychiat* 1952;**174**:153-68.
- Donald I, MacVicar J, Brown TG. Investigation of abdominal masses by pulsed ultrasound. *Lancet* 1958;**i**:1188-94.
- Edler I. Diagnostic use of ultrasound. *Acta Med Scand [Suppl]* 1955;**32**:306-8.
- Edler I, Gustofson A. Ultrasonic cardiogram in mitral stenosis. *Acta Med Scand* 1957;**159**:85-90.
- Moss AJ, Bruhn F. The echocardiogram: an ultrasound technic for the detection of pericardial effusion. *N Engl J Med* 1966;**274**:380-4.
- Popp RL, Harrison DC. Ultrasound in the diagnosis of and evaluation of therapy of idiopathic hypertrophic subaortic stenosis. *Circulation* 1969;**40**:905-14.
- Wolfe SB, Popp RL, Feigenbaum H. Diagnosis of atrial tumours by ultrasound. *Circulation* 1969;**39**:615-22.
- Allan LD, Tynan MJ, Campbell S, Wilkinson JL, Anderson RH. Echocardiographic and anatomical correlates in the fetus. *Br Heart J* 1980;**44**:444-51.
- Blumgart HL, Weiss S. Studies on the velocity of blood flow. *J Clin Invest* 1927;**4**:15-31.
- Rejali AM, MacIntyre WJ, Friedell HL. Radioisotope method of visualisation of blood pool. *Am J Roentgenol* 1958;**79**:129-37.
- Anger HO. Gamma ray and positron scintillation camera. *Nucleonics* 1963;**21**:56-7.
- Bonte FJ, Christensen EE, Curry TS. Technetium-99 pertechnetate angiocardiology in the diagnosis of superior mediastinal masses and pericardial effusions. *Am J Roentgenol* 1969;**107**:404-12.
- Kety SS. Measurement of regional circulation by the local clearance of radioactive sodium. *Am Heart J* 1949;**38**:321-8.
- Cannon EJ, Dell RB, Dwyer EM. Measurement of regional myocardial perfusion in man with ¹³³Xenon and a scintillation camera. *J Clin Invest* 1972;**51**:964-77.
- Holman BL, Sporn V, Jones AG, et al. Myocardial imaging with technetium-99m CPI: initial experience in the human. *J Nucl Med* 1987;**28**:13-8.
- Jones T. Positron emission tomography. *Br Med Bull* 1980;**36**:231-6.
- Gorter CJ. Negative results of an attempt to detect nuclear magnetic spins. *Physica* 1936;**3**:995-8.
- Purcell EM, Torrey HC, Pound RV. Resonance absorption by nuclear magnetic moments in a solid. *Phys Rev* 1946;**69**:37-8.
- Bloch F, Hansen WW, Packard M. Nuclear induction. *Phys Rev* 1946;**69**:127.
- Radda GK. Potential and limitations of nuclear magnetic resonance for the cardiologist. *Br Heart J* 1983;**50**:197-201.
- Lauterbur PC. Image formation by induced local interactions: examples employing nuclear magnetic reso-

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- nance. *Nature* 1973;242:190–1.
- 45 Damadian R, Goldsmith M, Minkoff L. NMR in cancer: fonar image of the live human body. *Physiol Chem Phys* 1977;9:97–108.
 - 46 Underwood SR, Rees RSO, Savage PE, *et al.* Assessment of regional left ventricular function by magnetic resonance. *Br Heart J* 1986;56:334–40.
 - 47 Ridgway JP, Smith MA. A technique for velocity imaging using magnetic resonance imaging. *Br J Radiol* 1986;59:603–7.
 - 48 Klipstein RH, Firmin DN, Underwood SR, Nayler GL, Rees RSO, Longmore DB. Colour display of quantitative blood flow and cardiac anatomy in a single magnetic resonance cine loop. *Br J Radiol* 1987;60:105–11.
 - 49 Been M, Ridgeway JP, Douglas RHB, *et al.* Characterisation of acute myocardial infarction by gated magnetic resonance imaging. *Lancet* 1985;ii:348–50.
 - 50 Muir AL, Smith MA, Been M, *et al.* Sequential changes in T_1 in man following acute myocardial infarction. Book of Abstracts Fifth Annual Meeting Society of Magnetic Resonance in Medicine 1986;1:237–8. Berkeley, California: Society of Magnetic Resonance in Medicine.