Reviews in Medicine

Medical imaging

Louis Kreel

Department of Diagnostic Radiology, Prince of Wales Hospital, Shatin, N.T., Hong Kong

Introduction

Physicists have tapped the electromagnetic spectrum to great effect. Each energy wave-form that penetrates tissues has a corresponding imaging system, starting with Roentgen's radiograph of his wife's hand in 1895. Since then gamma rays, X-rays, protons, ultrasound and radiofrequency coupled to a magnetic field have been grafted onto computers to produce anatomical images varying in type and detail. More recently these modalities have produced sophisticated physiological data of considerable interest.

Thus the words 'digital' and 'computer' have invaded radiology departments, not only with scanners, of which they are integral components, but also in conventional fluoroscopy and radiography. The change is as revolutionary as that of steam engine to internal combustion engine or automobile to aeroplane. The costs too are comparable for the equipment, although in the long run the cost of patient care will remain unchanged or be even less if the rapidity and accuracy of diagnosis is taken into consideration.

So much for analogies. What, then, in broad outline is new? PACS, the picture archiving and communications systems, if fully operational, will create hospitals without radiographic film. Images will be transmitted instantaneously within hospitals, between hospitals, across the country and between continents, with greater contrast and resolution by tele-video communication. Archiving and recall will also be nearly instantaneous. In addition, the clinical details, biochemistry and available pathology will appear on the screen. Radiology departments will become diagnostic departments of medical imaging.

In the interim, conventional radiography is being automated, with radiographers concentrating on the patient's well-being, on reassuring the patient and on careful positioning. The radiographs will be processed in daylight, having greater definition and

latitude with lower radiation and minimal repeat examinations. Dark rooms for film processing will disappear. Fluoroscopy too will be fully automated and digitized, and all radiographs will show the full range of radiodensities from lung, through soft tissues to bone with one exposure. This will entail new equipment, film, cassettes and imaging systems at considerable expense.

Furthermore, each passing year sees the introduction of new scanners with shorter scanning times and higher spatial resolution, producing greater detail and more information. Millisecond computed tomography (CT), cardiac cine, magnetic resonance imaging (MRI) down to breath-holding time, and the technology of CT applied to nuclear medicine (NM), yielding single photon emission CT and proton emission tomography, are now available.

With this equipment and the development of new radionuclides as well as MRI spectroscopy, which is at present being evaluated in clinical practice, windows to cerebral activity in health and disease have been opened. The research emphasis in imaging is thus changing from morphology to function, particularly in the heart and brain.

However, the great and elusive goal of tissue characterization has not been fulfilled with either CT or MRI. The search continues with magnetic resonance spectroscopy (MRS) in the hope of distinguishing granulomas and tumours, benign from malignant, or even to go further by assessing the degree of malignancy. The ultimate aim of diagnostic imaging then is to produce complete morphological and functional information, thereby equalling the achievements of histology. MRS and NM individually or in combination are also being applied to metabolic diseases.

The magic and art of imaging resides with sonography, where the hand-held probe sees directly into the body, now extending its scope even further with colour Doppler, endoscopic sonography and peroperative applications.

As the centenary of Roentgen's discovery approaches we can perceive how X-rays are slowly

but surely being ousted from their pre-eminent position in medical imaging, giving way to non-ionizing electromagnetic energies. In fact it is extremely doubtful if a modern ethical committee would allow the use of X-rays in clinical practice if presented as a new discovery. On the basis of animal experiments the effects of X-rays would probably be considered unacceptable. In the history of medical imaging the 20th century may well be designated as the century of iatrogenic radiation, medical imaging having replaced radiology.

The radiology department

The production, filing and delivery of radiographs to the wards, out-patient department and theatre are tedious and labour-intensive tasks. Subsequently their retrieval for re-filing is often difficult and fraught with recriminations: the vital and interesting film is always the one that is missing or lost. Storage of film requires a large space, particularly as radiographs must be kept for at least 7 years. Many departments and hospitals would like to have follow-up studies for even longer periods, especially orthopaedic surgeons and chest physicians. Frequently operations and consultations cannot proceed without the relevant films. This holds true also for interdisciplinary case presentations, particularly for tertiary referrals. Furthermore, transmitting radiographic information verbally or in writing is often ambiguous. Picture archiving and retrieval systems (PACS)¹⁻³ can eliminate these difficulties, but require the data in digital form.

Most medical images are or can be digitized, including not only NM, CT, MRI and obviously digital subtraction angiography (DSA) but also, in the not too distant future, plain film radiography. Digital images have many advantages for viewing, storage, retrieval and transmission.

The image on a video monitor can be modified in a number of different ways and interrogated. Part or all of the image can be enlarged or diminished, measured, annotated, reversed, and windowed to show the different tissue densities of bone, soft tissue or lung, and these densities can be measured. Sectional images can be reconstructed into other planes or into D-3 and optimized for spatial and contrast resolution. Hard copy of these images is frequently a poor substitute for viewing the images on a monitor, resulting in a loss of important information. The small subdural haematoma is an example. Unless the CT sections are shown at a wide window, it will be indistinguishable from bone. There are a number of other techniques that also depend on the manipulation of digital data, such as cardiac and respiratory gating and forming cine loops for dynamic studies.

Video consoles are an essential component of all scanners. The images are seen in real time during sonography, almost in real time with the newest CT and MRI equipment, then shown as static images for interrogation or as a dynamic cine loop study. Nuclear medicine and Doppler sonography are often shown in colour. Yet very few departments have a central viewing area where the various images can be integrated.

At present, then, these video consoles are part of the equipment used during the examination or only within the confines of the particular diagnostic suite and are not available for interdisciplinary consultations when the information from 2 or more examinations needs to be correlated, especially angiography and CT or the various sequences of MRI. The correlation of sonograms with other scanning procedures and isotope scans with plain films are other examples. The advantages for consultations and teaching are self evident.

A system that will permit the simultaneous viewing and integration of the various images necessitates their on-line transmission to a central archive whence they can be viewed at one or more areas such as a consultation studio or the surgical operating suite. In the first instance the images must be available to radiologists for their immediate assessment to conclude the examination and for reporting. Simultaneously the images are stored in the central archive where the various modalities are integrated for future display.

To be effective the archive must be able to hold the vast amount of information and to reformat the image. Either more powerful computers are needed or there must be compression of the images but with no loss of detail. Such compression systems have now been produced with ratios of 5–10:1.⁴

The transmission of medical images from one location to another is called teleradiology⁵ and wide area networks are already in existence. A laser film digitizer with an optical disc and a laser printer are essential for high-quality images. A variety of technologies are used for the communication network, including co-axial cables, fibre-optic links, switched circuits and satellite transmission providing immediate images to the accident and emergency department and intensive care unit. Outlying hospitals or clinics can communicate with their large central counterparts or academic institution before admission is arranged.

In the United Kingdom and many other countries these major developments will concern only a small number of institutions. Many more will be affected by the prospect of the greater resolution to be obtained with conventional radiographic equipment.⁶⁻⁸ In one system the film itself has been changed and in the other radiographic film has been discarded in capturing the initial image. A radiographic image is produced by transmitted

X-rays falling on halide crystals in the emulsion of the film after the fluorescent screens in the cassette have been activated. In the Kodak system the crystals are flat and polygonal, producing a much larger surface area to receive the incoming photons and hold the image. This film is combined with rare-earth phosphor fluorescent screens to produce a green light-sensitive system. The resulting radiograph has better definition and increased dynamic range, allowing visualization of both the mediastinum and the lungs on a chest radiograph. In a further development the advanced multiple beam equalization radiography (AMBER) system uses a rectangular multi-X-ray beam to scan the thorax. The wide range of radiodensities is equalized by a microprocessor. The system also requires a 3-phase generator with an output up to 150 kVp and an 0.8 second exposure.

With their FCR 7000 system Fuji have gone one step farther and eliminated the film in capturing the initial image by using computed radiography and high-sensitivity plates read by a high-precision spot laser system. The image can then be transmitted to a video console or printed out on film as a radiograph that shows both soft tissues and bone on one film, or two films can be processed simultaneously. The films have greater definition and the radiation dose is reduced to 10% of a conventional chest radiograph.

The cost of immediate replacement of the present radiographic units by these newer systems would be beyond the UK National Health Service in the present financial blight but might be achieved as existing equipment wears out. However, the much lower radiation dose is a powerful argument for an immediate change in paediatric examinations.

Sonography

Ultrasound examinations are fast and inexpensive but are much more dependent on the operator than other scanning methods. They are particularly useful for localizing mass lesions, whether cysts, abscesses, granulomas or tumours, benign or malignant, and for percutaneous aspiration, cytology and biopsy.⁹⁻¹⁴ Newer units have much better definition, providing more accurate diagnosis.

In recent years sonography has to a large extent replaced contrast examinations of the gall bladder¹⁵⁻²⁰ and genito-urinary tract²¹⁻²³ and is in most instances more helpful in the abdomen than plain film radiography.²⁴ Sonography has an important advantage over radiography in that it is a non-ionizing form of radiation.

While gas and bone cannot be penetrated by ultrasound, there are still many indications for its use in the thorax in addition to sonocardiography, and it is especially indicated prior to tapping of

pleural effusions. The fluid acts as a window to underlying lung and mediastinal disease for consolidation, collapse and tumours.^{25,26} In localized pleural disease small effusions can be distinguished from solid lesions, and ultrasound is also ideal for accurate percutaneous aspiration or biopsy.

Transthoracic cardiac sonography²⁷⁻³¹ is used in valvular disease, pericardial effusions, myocardial motion studies and septal defects. The scope of sonocardiography has been increased with colour Doppler, which reveals the direction of blood flow. Intracardiac shunts and valvular disease can be assessed more accurately. Transoesophageal sonography has proved itself in the diagnosis of aortic lesions, particularly aortic dissection,³² as a rapid, accurate method that also gives a good view of the left atrium, left atrial appendage and left ventricle. Intra-operative sonography allows accurate assessment of the aortic and mitral valves necessary for decisions on whether to perform valvulotomy, valvuloplasty or valve replacement.

Transoesophageal sonography is at present the best method for staging oesophageal carcinoma,³³ particularly in assessing the depth of tumour invasion and the presence of lymphadenopathy, and can also show whether sclerotherapy or varices has been effective. Further down, transgastric sonography is similarly effective for gastric tumours³⁴ and also in pancreatic tumours including insulinoma. Recent reports indicate that intra-operative sonography has a high accuracy in locating a deeply seated endocrine tumour shown as a well-circumscribed hypoechoic area within the pancreas.³⁵

Sonography is indissolubly linked to the modern practice of obstetrics and gynaecology.³⁶ In obstetrics the fetus and placenta can be imaged almost from inception to parturition, and assessment can be made of fetal gestational age, growth and viability, multiplicity, fetal abnormalities and placental localization, texture and transplacental haemorrhage. Internal pathology such as pelvic masses can be diagnosed. The most remarkable images are produced by transvaginal sonography showing the ovaries, adnexae and uterus in great detail, which is extremely useful in the diagnosis of ectopic pregnancy.³⁷⁻³⁹ If pregnancy is confirmed by the sensitive and specific radioimmunoassay for the beta subunit of human chorionic gonadotrophin (β -hCG), intravaginal sonography with Doppler can exclude an ectopic pregnancy by locating a gestational sac within the uterus, and it can be distinguished from a pseudogestational sac by its frequency shift. Other signs such as pelvic fluid and endometrial changes are not helpful. The actual ectopic pregnancy in the adnexae can be visualized in about 40% of patients found to have an ectopic pregnancy at surgery.

Transvaginal endosonography is also consid-

erably more accurate than transabdominal sonography for staging of cervical carcinoma and in assessing the ovulatory cycle for *in vitro* fertilization. At the time of oocyte transfer, transvaginal sonography allows harvesting of oocytes by accurately localizing the ovarian follicle.⁴⁰

The advantages of transvaginal sonography are manifold. The uncomfortable fully distended bladder is no longer necessary, reducing waiting time for patients. The high-frequency (6 MHz) pencil-shaped probe has an effective focal zone of up to 8 cm, producing excellent detail, earlier recognition of the fetal heartbeat and recognition of a non-viable pregnancy. Advanced masses are more accurately assessed.

Transrectal sonography for anorectal⁴¹ and prostatic^{42,43} carcinoma is equally effective for tumour localization and staging. The peripheral, central and transitional zones of the prostate can be identified with the 5 and 7 MHz probes as hypo-echoic areas. The zonal concept of McNeal⁴⁴ is extremely important as 70% of tumours occur in the peripheral zone and only 15% in the inner transitional zone. Under antibiotic cover transrectal biopsy is safe provided there is no evidence of active infection and no bleeding tendency. It is probably at present the best screening technique with a specificity of about 95%.

Transcutaneous sonography of the abdomen for liver, pancreas, spleen, gall bladder and kidneys is well established and needs no further emphasis, apart from stressing its role in abscess localization and drainage, especially peri- and intrahepatic collections, and in percutaneous cytology and biopsy.⁴⁵⁻⁴⁷ However, there is a definite role for sonography in and around joints, tendons and muscles. Joint effusions, capsular thickening, tendinous tears, calcification, muscle tumours, haemorrhage and abscesses can be displayed. In the shoulder impingement syndrome the fluid collections in the subdeltoid-subacromial bursal system and the lateral pooling of fluid in the subdeltoid part when the arm is raised are diagnostic.^{48,49}

Colour Doppler has been mentioned for cardiac lesions, and now with pencil or annular phased array probes (5–10 MHz) dynamically focused with a symmetrical cylindrical beam blood vessel imaging becomes even more accurate. Pulmonary emboli from deep venous thrombosis are an ever-present hazard in hospital whether in post-surgical or medical patients. Non-invasive techniques, if effective, must take precedence over contrast venography, and Doppler sonography is proving itself in this sphere.⁵⁰⁻⁵² The aorta and its major branches, renal, mesenteric, coeliac axis, hepatic and iliacs, and the measurement of portal blood flow⁵³ can be imaged and interrogated for blood-flow data. Doppler is valuable in the differential diagnosis of tumours by demonstrating the vas-

cular pattern as in hepatomas.⁵⁴

Sonography is especially valuable in paediatrics not only because there is no radiation hazard, but also because it is non-invasive, rapid and accurate and can be applied to all anatomical areas including the scrotum for the diagnosis of testicular torsion.⁵⁵ Children have the ideal combination for ultrasound because of their poorly developed fat planes and small size. Furthermore, the reassuring parent can be close to the child.

Sonography, therefore, if used wisely and well, becomes the most commonly used and most versatile scanning procedure, with a constantly increasing scope especially in neonatal practice and in the intensive therapy unit. It is the only portable scanning method that can be used in the operating theatre to localize brain pathology,⁵⁶ on restless ill patients that cannot have CT or MRI, and on premature babies on life-support systems.⁵⁷

The magic and art of imaging resides in the ultrasound suite.

Computed tomography

As the name implies, CT could not exist without computers. Simply stated, a rotating X-ray tube provides an X-ray beam that passes through the body stimulating an array of detectors. The absorption of the X-rays within the body or attenuation of the beam can be calculated from the difference between the entering and emerging photons, and by Fourier transform the attenuation of each small volume or voxel or tissue can be computed and localized within a section of the body.⁵⁸

The digitized information is then converted into an anatomical image, almost always in the axial plane except in the skull, where coronal sections are used especially to display the orbits, pituitary and paranasal sinuses.

The image is displayed on a video console and can be manipulated or interrogated because the information is essentially digital. By 'windowing' the image the grey scale can be changed to produce either greater or lesser contrast or spatial resolution and can be set for tissues of varying radiodensity. The same data can then be used to show the full range of tissue attenuation from lung through fat, water and soft tissues to bone without rescanning the patient. Many other manipulations can also be done, such as obtaining the actual attenuation values in Hounsfield units, measuring distances and areas, using special programmes for bone detail and for reconstruction into coronal and sagittal planes. These facilities with CT have been available for about 15 years since the first body machines were produced that could scan within breath-holding time, i.e. about 18 seconds.⁵⁹

More recent refinements include scanners that produce an image in 1–2 seconds, completing an examination of the abdomen or thorax in 8–20 seconds with almost simultaneous or on-line display of the images. Reconstruction into 3-D, creating holistic images, is a still more recent development that offers the ability to view from any angle and show the various anatomical layers without superimposed tissue.

Quite recently CT equipment has been produced with no moving parts by means of the principle of the 'electron gun'. Focused electrons strike an array of targets that send the photons through the body to the detectors. With this system images can be produced in milliseconds and a whole examination can be completed in seconds, ideal for contrast studies of the heart.⁶⁰ A further innovation is the introduction of thin section CT of 1–2 mm in conjunction with scan times of 1–2 seconds. The resulting lung images have exquisite anatomical detail.⁶¹

The most significant drawback of CT is that contrast medium is needed to show the cardiovascular system. While CT equipment is about half or two-thirds of the price of MRI, it is some 5–10 times the price of sonographic equipment. Maintenance costs have a similar differential. However, CT images are immediately recognizable, as the organs are well demarcated by fat planes, the bowel can be labelled with oral contrast medium, and the appearance of the skeleton is similar to that seen on conventional radiographs. Both sonographic and MRI images are totally different from each other and unlike CT are not immediately recognizable as anatomical sections.

CT has been accepted by all the medical specialties as an important diagnostic tool, most of all for neurologists and oncologists as it can be and has been applied to all parts of the body.^{62,63} The main limitation, as with all imaging systems, is the inability fully to characterize tissue, particularly in distinguishing benign and malignant lesions – a recurring problem in the treatment of tumours. The residual tissue after radiotherapy or chemotherapy is readily demonstrated by CT but fibrosis and viable tumour appear similar. Further management relies on a 'wait and rescan' policy, surgical excision or percutaneous biopsy.⁶⁴

Interstitial lung disease has an extensive differential diagnosis including sarcoidosis and other granulomatous diseases, allergy, collagen vascular disease, haemosiderosis, proteinosis and malignant infiltration. With thin section CT of 1–2 mm, using the bone algorithm and a scan time of 1–2 seconds the secondary lung lobule can be visualized⁶⁵ with a central dot representing the centrilobular artery and bronchus. The outer polyhedral margin of connective tissue contains the veins and lymphatics.

Interstitial lung disease can now be categorized by the axial distribution, by the appearance of the abnormal densities and by the effect on the secondary lobule.⁶⁶ As a practical detail, perihilar or central disease requires transbronchial biopsy, mid-lung disease requires open lung biopsy, and peripheral disease can be diagnosed by percutaneous lung biopsy. The distribution of bullous emphysema is clearly visible.

On the basis of chest radiography and thin section CT, pulmonologists now describe abnormalities as linear, reticular, nodular, reticulo-nodular, ground glass, homogeneous or honeycomb. Their distribution is referred to upper, middle and lower zones as well as to peripheral (cortex), middle or hilar (together forming medulla). The more accurate localization, the earlier detection⁶⁷ and more exact descriptive terminology constitute a major advance in chest radiology and pulmonary diagnosis.⁶⁸

The ultrafast CT scanner (Imitron) can produce an image in 50 milliseconds and complete an examination of the heart in under 1 second, taking 17 sections per second to produce cardiac cine in real time.^{69,70} Ventricular motion, cine-angiography and ejection fractions⁷¹ can therefore be studied by CT with great accuracy, which is especially valuable in assessing cardiac shunts⁷² and patency of coronary by-pass grafts. Very early coronary artery calcification can also be detected, said to predict the presence of coronary artery stenosis. Aortic dissection is well demonstrated by fast scanners that have a further advantage: much less contrast medium is needed and can be given as a single bolus without the need for a multiple bolus technique or rapid drip infusion.

The most important development in CT technology, however, is the production of a cheaper versatile model, more compact, that no longer requires a separate air-conditioned room for the computer. Computed tomography becomes a reality for small general hospitals.

Magnetic resonance imaging

Sonography is at the lower end of the cost spectrum in imaging and MRI at the uppermost. Yet in the United States there is ready access to this equipment, particularly in the major academic institutions and in private clinics, resulting in an extensive literature. The technology is ever expanding.

MR images are produced by the combination of a magnetic field and a radio-frequency pulse. As in sonography, the pulse generator also acts as the receiver. Three types of magnet, permanent, resistive and cryomagnet,⁷³ varying in strength from 0.1 to 2 Tesla are available and vary in cost from £0.75

million to £2.0 million. The radio-frequency coils are either large body coils or small and localized to fit specific anatomical areas. The computer software creates the pulse sequences to form the images.⁷⁴

In brief, within the body, the protons of the water molecule act as magnets, normally in a random distribution. When in the MR magnet the protons are aligned in the direction of the magnetic field with a spinning motion. These spinning protons can be flipped to a right angle, to 180° or to angles in between by a radio-frequency pulse, after which the protons will return to their resting position. In so doing they give off a signal captured by the radio-frequency coil. These impulses are then processed to form an image by a mathematical technique known as the Fourier transform.⁷⁵

The exponential decay of the spinning protons produces a variety of signals depending on the sequence of radio-frequency pulses. If the proton decay is a simple repolarization or free induction decay, the signal then represents only proton density. After a 90° pulse followed by a 180° pulse, the signal is captured from the spin-echo. Differing relaxation properties of tissues and fluids can be calculated to produce different images. If the interval between 90° pulses (repetition time or TR) is short and the time between the measured echoes (SE or spin echo) is also short, T₁ relaxation times will be recorded, whereas if these times are long then T₂ relaxation times are produced.⁷⁶

T₁ and T₂ images are markedly different. In broad terms, T₁ or spin-lattice images have more anatomical detail, while T₂ or spin-spin images have considerably more contrast between different tissues, particularly between normal and abnormal soft tissues. Fat and recent haemorrhage are white or of high signal intensity (SI) on T₁-weighted images (T₁-WI) and medium to high signal intensity on T₂-WI. Cysts or old haemorrhage have low SI (black) on T₁-WI and white on T₂-WI. Bone and gas produce no signal (signal void).⁷⁷

Recently new sequences have been developed that change the signal intensities or markedly alter the scanning times, hence the large number of acronyms – STIR, GRASS, FLASH,^{78,79} FAST, FISP, SPEED and RARE,⁸⁰ to mention some. STIR,⁸¹ or short time recovery, is of interest as the fat signal is suppressed showing a medium signal intensity, unlike T₁ and T₂-WI. With GRASS, or gradient-echo recalled acquisition in a steady state, a gradient radio-frequency pulse is followed by small angle pulses to produce images within breath-holding times. However, various artifacts can occur with these sequences such as black margins and even pseudo-lesions. With RARE⁸⁰ (rapid acquisition relaxation enhanced) sequences produce T₂-WI much more rapidly, 16 images within 2 minutes.

The value of MRI was recognized immediately when demyelinating lesions were demonstrated that were not seen with CT, especially in multiple sclerosis.⁸² Other advantages were also obvious. The regions abutting bone, the cerebral cortex, base of brain, and the posterior fossa were shown quite clearly, whereas with CT these areas are poorly demonstrated, often by superimposed artifacts from adjacent bone. Direct sagittal and coronal MR images are very useful in localizing lesions and demonstrating small structures such as the optic chiasma and tracts, intracranial vestibular nerve and pituitary gland.^{83–85}

The spinal cord, pons and medulla can be seen separate from the surrounding thecal sac and cerebral spinal fluid.⁸⁶ Sagittal sections show the whole length of the cord for the diagnosis of cerebellar tonsil herniation, syringomyelia, intramedullary tumours and disc herniation and prolapse. In the vast majority of cases contrast myelography will not be needed where MRI is available,^{87,88} and is the method of choice in evaluating spinal trauma.^{89,90}

The bone marrow is another area where MRI exhibits new imaging information.^{91,92} Although the surrounding bone has no signal – ‘signal void’ the imaged bone marrow reflects its changing pattern due to aging. In children and young adolescents active red marrow in both the peripheral and axial skeleton has low signal intensity on T₁-WI, gradually changing to high intensity in the peripheral skeleton as fatty marrow supervenes. The femoral epiphysis and greater trochanter have high signal intensity in adolescents, with the shaft and neck of femur changing to high intensity on T₁-WI in the middle aged and elderly. The spine is of low intensity in children apart from the horizontal area around the basivertebral veins. With age this region changes to low intensity, while the rest of the vertebral body develops spotty or patchy areas of high intensity. Similar changes occur in the skull: the frontal and occipital regions develop intense signals and the parietal region lagging with mixed low and high intensity areas, until in middle age the whole cranial vault has high intensity signals on T₁-WI.

It is difficult to detect diffuse bone marrow infiltration in childhood but in adults, particularly in the elderly, the replacement of fatty marrow by carcinoma metastases, lymphoma or myeloma is readily demonstrated, unlike isotope bone imaging where lymphoma and myeloma cannot usually be shown.

MRI is being used extensively in orthopaedic practice for a variety of conditions ranging from ligamentous and meniscal trauma,⁹³ osteonecrosis, especially avascular necrosis of the hip^{94,95} and scaphoid, and capsular degeneration of the shoulder,⁹⁶ to the bone bruise that is not visible on

plain radiographs or on CT. Orthopaedic implants such as hip prostheses are *not* a contraindication for MRI.⁹⁷ There have been no reports of unsafe tissue heating nor has there been any evidence of torque. While there is focal loss of signal and some distortion may occur, CT has considerably more artifacts in the form of radiating streaks from implants. MRI in the presence of orthopaedic implants thus has a distinct advantage over CT. Soft tissue tumours are more clearly delineated than on CT.⁹⁸

MR images of the heart and great vessels are truly remarkable,⁹⁹ showing even more than sonography but at considerably more cost. The major advantage is that chronic obstructive airways disease is not an insuperable barrier nor are calcified costal cartilages or ribs. MRI has the advantage over CT as contrast medium is not required and the heart and great vessels can be shown directly from any angle.

MRI displays pericardial, myocardial and valvular disease¹⁰⁰ as well as abnormalities of the great vessels with the aid of the cardiac and respiratory gating.¹⁰¹ Stroke volume and ejection fractions can be determined and areas of dyskinesia can be visualized.¹⁰² Cardiologists and cardioradiologists now have the possibility of discarding catheter examinations except for coronary angiography and angioplasty. Similarly, contrast angiography may become superfluous as modifications to MR angiography produce more detailed images of the vascular system. At present the arterial system is shown as having high intensity signals and appears similar to conventional contrast angiography.¹⁰³ With this MRI technique stenoses are exaggerated due to distal turbulence and severe stenoses cause poor flow contrast. These artifacts can be eliminated by using 'black blood' MR angiography where the proton signals appear hypointense.¹⁰⁴

MRI also has a place in the diagnosis of pelvic masses during pregnancy if further information is required following sonography.¹⁰⁵

Magnetic resonance spectroscopy

In vivo biochemical analysis of tissues can be obtained from nuclei with an odd number of protons or neutrons (¹H, ³¹P, ¹³C, ²³Na and ¹⁹F) that exhibit nuclear magnetic resonance (NMR), because the resonance frequency of a particular nucleus is affected by its chemical environment in a way that allows it to be measured.¹⁰⁶ Thus, the NMR signal depends on the gyrometric ratio of the nucleus and on the intensity of its magnetic field. The magnetic field of the nucleus in turn depends on the external magnetic field applied by the magnet as well as the surrounding electrons and the electrons of adjacent atoms. It is the interaction of

the electrons with the external field, changing the field around the nucleus, that produces 'chemical shift' forming the basis of MR spectroscopy.

MRS is obtained with apparatus similar to MRI but requires an extremely homogenous external magnetic field. In a similar way brief pulses of radio-frequency excite the nuclei.¹⁰⁷ This is followed by a period of signal acquisition. The acquired signal obtained by free induction decay (FID) is Fourier transformed to produce a spectrum in which chemicals in solution form narrow peaks. The area under the peak depends on the number of nuclei detected. The position in the spectrum identifies each particular metabolite. A broad range of frequencies is generated by MRS to study nuclei with very differing resonance frequencies, including ³¹P to detect ATP, PCr and Pi inorganic phosphorous as an indicator of pH; ¹H measures lactates; ¹³C is used for glycogen, some lipids and compounds using ¹³C-labelled metabolites.¹⁰⁸

Cardiac and voluntary muscle can be analysed with MRS. During muscular contraction there is a rapid fall in phosphocreatine (PCr), a rise of Pi and an acid shift of the Pi peak. Only when PCr is virtually depleted does the ATP peak change, indicating a single pool of PCr (CK).¹⁰⁹ Similar studies have been done on brain,¹¹⁰ kidney, liver and bowel. MRS of malignant tumours suggests it may be useful in monitoring the effects of treatment, providing an early indication of its efficacy¹¹¹ and possibly earlier diagnosis of the presence of malignancy from blood samples.¹¹² This has not as yet been achieved.

Nuclear medicine

Two separable aspects are integrated to form an image in NM, the recording device and emission of radiation from within the body. Recently, as in other scanning methods, computers have been added, increasing the resolution of the system for the detection of smaller lesions and to perform metabolic studies, particularly of the brain.

Over decades the hand-held scintillation detector has been replaced by the rectilinear scanner and later by the Anger gamma camera. A gamma camera consists of discrete photomultipliers each receiving the impulses from the sodium iodide crystals of the scintillation detector to convert the gamma photons from radionuclides within the body into electrical impulses that are then recorded individually, forming dots on a video monitor. The image can also be recorded on radiographic film.

In emission CT an injected radionuclide is the internal source of radiation, unlike X-ray CT where the source of radiation is an external beam, i.e. transmission CT. Single photon emission com-

puted tomography (SPECT) images are produced by a single- or dual-headed camera that rotates about the body through either 180° or 360° using computers to reconstruct an image in the axial plane. Dual-headed cameras produce better quality images; recently a 3-detector gamma camera (IGE neurocam) has been evaluated.¹¹³

SPECT¹¹⁴ effectively provides greater resolution and therefore more detailed information using conventional radionuclides based on ^{99m}Tc (technetium pertechnetate), ¹²³I, ¹³¹I and ¹¹¹In (indium) such as IMP (¹²³I p-iodoamphetamine) and HMPAO (^{99m}Tc hexamethylpropylene amine oxime) for cerebral metabolic studies.

Positron emission tomography (PET),¹¹⁵ on the other hand, is based on a quite different principle. The process relies on positron decay to form high-resolution NM images. A cyclotron is the energy source to produce short half-life radionuclides. As their unstable nuclei decay to a more stable state they emit positively charged electrons (positrons) and when these positrons combine with an electron their mass is converted into electromagnetic radiation by 'annihilation' producing a pair of high-energy photons (511 KeV). These two annihilation photons are emitted in opposite directions, falling simultaneously on detectors on opposite sides of the patient. In fact there is a ring of detectors to create an axial tomographic image of 1–2 cm somewhat similar to MRI and CT. PET has been used mainly to study brain metabolism, blood flow, tissue pH and cerebral blood volume using positron-emitting isotopes such as ¹³C, ¹³N, ¹⁵O, ¹⁸F and ⁶⁸Ga.

Both SPECT and PET can detect and localize diffuse and focal cerebral abnormalities producing metabolic and perfusion defects through abnormal isotope uptake.¹¹⁶ A variety of diseases¹¹⁷ have been studied including Alzheimer's, Pick's, Creutzfeld–Jacob, schizophrenia¹¹⁸ and cerebrovascular disease where regional blood-flow changes have been noted. Perfusion asymmetries appear to be more marked in presenile than in old-age onset dementias and greater in the more severely affected. Epileptic foci can be detected but for accurate pre-operative localization the PET image must be integrated with MRI or CT 3-D reconstructions if surgery is required for uncontrollable seizures.¹¹⁹

The development of new radionuclides increased the scope and potential of NM imaging. Outstanding among these are the isotopic monoclonal antibodies (MoAbs) that can target specific tissues for both diagnosis and treatment.¹¹¹ Indium-labelled antimyosin (Myoscint) for myocardial necrosis was the first to be used in clinical practice for diagnosis, prognosis and complications and to evaluate therapy.¹²⁰ It is especially valuable in patients with chest pain without classical ECG patterns of myocardial infarction or elevated

enzymes.

Biocompatible MoAbs have also now been developed to locate tumours by being tagged with ^{99m}Tc, ¹³¹I, ¹²³I and ¹¹¹In. ^{99m}Tc is favoured because larger doses can be used, allowing for earlier imaging with conventional gamma cameras (4–8 hours). ¹¹¹In has a longer half-life of 2–3 days, required when there is slow clearance of the antibody from the vascular spaces and interstitial tissues.

Radioimmunochemistry, as it is now called, has been used successfully in imaging metastases from melanoma and colorectal and ovarian carcinoma, and in the diagnosis of primary ovarian cancer, as well as in infections and vascular thrombi.^{121,122} The procedure is safe with a high degree of specificity for the detection and staging of disease whether benign, malignant, infective or metabolic. Recently systemic amyloidosis has been imaged; the deposits were rapidly and specifically localized with ¹²³I-labelled serum amyloid component.¹²³ As is to be expected, the detection rate of lesions shown by radioimmunochemistry can be increased by imaging with SPECT

Digital subtraction angiography (DSA)

The advent of scanning of all forms has diminished the diagnostic role of angiography but it remains essential for interventional procedures to correct or ameliorate vascular pathology and also as a road map, particularly in transplant surgery. Angiography with DSA is safer and more rapidly performed.¹²⁴

The principles of subtraction radiography were described by Ziedses des Plantes more than half a century ago. A separate image is produced of the difference between two radiographs by covering one radiograph with the diapositive of the other, now readily accomplished by computation with digitized images. Immediately prior to the contrast medium being injected a baseline image is taken. The digital data of this image is subtracted from the subsequent images as they appear on the monitor. A hard copy of the most diagnostic image is then processed on radiographic film and/or stored on disc or tape.

The aorta, pulmonary vessels and large arterial branches, including the carotids, vertebrals, cerebral, renal and mesenteric branches, can be shown from an intravenous injection into the superior vena cava or into the right atrium.¹²⁵ Intravenous DSA has the obvious advantage of not requiring an arterial puncture but it does need a large volume of concentrated contrast medium. Furthermore there must be no movement of the patient during the procedure, necessitating the use of contrast medium that produces little or no side effects,

namely expensive non-ionic contrast medium.

If the examination is performed by an arterial catheter, placing the catheter in the aorta, considerably less and more dilute contrast medium can be used. Selective catheterization is usually not needed and can thus be performed more rapidly using only local anaesthesia and no or minimal sedation. With DSA there is considerably less radiation and much less film is used.

Intravenous DSA for suspected renal artery stenosis has the further advantage that a high-quality film of the kidneys and ureters can be obtained following the arteriogram by taking a single overcouch film of the abdomen and using the contrast medium of the arteriogram to provide an intravenous urogram.¹²⁶

Non-ionic contrast medium

The water soluble iodine contrast agents for intravenous and intrarterial studies are remarkably safe considering the amount of contrast medium injected per examination, varying between 20 and 50 g.¹²⁷ Fatalities have been reported as occurring in 1 in 40,000 patient injections but in a recent report there was not a single death in some 350,000 contrast studies. Patients with heart disease are particularly at risk of a severe reaction as well as those with asthma and allergy. A history of previous contrast reaction is especially important in this regard.

The major adverse reactions are related to the high osmolality of the ionic contrast agents affecting red blood cells, capillary endothelium, the blood-brain barrier and haemodynamics. Crenellated red cells produced by the high osmolality cannot pass through capillaries resulting in anoxia, especially damaging in sickle-cell disease. Capillaries become weakened, resulting in interstitial oedema, and damage to endothelium allows contrast medium to enter brain cells. Local vasodilatation tends to cause a feeling of warmth, and pain is not infrequent. General vasodilatation can cause hypotension and collapse, and hypervolaemia causes further myocardial strain.

Non-ionic contrast agents are relatively free of these effects, essential for contrast phlebography and for intravenous DSA in patients with heart disease and asthma; they are also recommended in diabetes and renal disease.

The only disadvantage of non-ionic contrast medium is the higher cost,¹²⁸ some 3–4 times greater in Europe but about 10 times greater in the USA where the cost of ionic contrast agents is considerably less. Non-ionic contrast agents are unlikely to become much cheaper in the immediate future because of the complexity of the production process.

Radiological screening programmes

Mass screening for gastric carcinoma with barium meal examinations in Japan was used to detect early surface lesions. Gastric surgery in those patients produced 90% 5-year survivals.¹²⁹ The results with mass screening for breast cancer are somewhat more controversial, although mammography is the only reliable method to detect occult breast carcinoma. Early detection is said to produce a 30–70% reduction in the chance of dying from the disease.¹³⁰ There is also no doubt that mammography can detect 90% of breast cancers, and of these 60% are infiltrating but less than 1 cm or are non-infiltrating tumours, compared with only 6% found by physical examination.^{131,132} Yet the evidence published by enthusiasts has been criticized, suggesting that, in fact, there is no hard evidence that breast cancer screening reduces mortality.¹³³

Although the breast is sensitive to X-rays there is no definite evidence of an increased risk of carcinoma resulting from breast screening. Nevertheless a film/screen combination providing the lowest exposure must be used but without sacrificing detail. This can be achieved with green sensitive film that has a double-sided emulsion and the new flat orthogonal silver halide grains.

Densitometry is now being suggested as screening for osteoporosis to identify women at risk who would benefit from hormone replacement or etidronate therapy.

Summary and conclusions

There is now a wide choice of medical imaging to show both focal and diffuse pathologies in various organs. Conventional radiology with plain films, fluoroscopy and contrast medium have many advantages, being readily available with low-cost apparatus and a familiarity that almost leads to contempt. The use of plain films in chest disease and in trauma does not need emphasizing, yet there are still too many occasions when the answer obtainable from a plain radiograph has not been available. The film may have been mislaid, or the examination was not requested, or the radiograph had been misinterpreted. The converse is also quite common. Examinations are performed that add nothing to patient management, such as skull films when CT will in any case be requested or views of the internal auditory meatus and heel pad thickness in acromegaly, to quote some examples.

Other issues are more complicated. Should the patient who clinically has gall-bladder disease have more than a plain film that shows gall-stones? If the answer is yes, then why request a plain film if sonography will in any case be required to 'exclude'

other pathologies especially of the liver or pancreas? But then should cholecystography, CT or scintigraphy be added for confirmation? Quite clearly there will be individual circumstances to indicate further imaging after sonography but in the vast majority of patients little or no extra information will be added. Statistics on accuracy and specificity will, in the case of gall-bladder pathology, vary widely if adenomyomatosis is considered by some to be a cause of symptoms or if sonographic examinations 'after fatty meals' are performed.

The arguments for or against routine contrast urography rather than sonography are similar but the possibility of contrast reactions and the need to limit ionizing radiation must be borne in mind. These diagnostic strategies are also being influenced by their cost and availability; purely pragmatic considerations are not infrequently the overriding factor.

Non-invasive methods will be preferred, particularly sonography as it is far more acceptable by not being claustrophobic and totally free of any known untoward effects. There is another quite different but unrelated aspect. The imaging methods, apart from limited exceptions, cannot characterize tissues as benign or malignant, granulomatous or neoplastic; cytology or histology usually provides the answer. Sonography is most commonly used to locate the needle tip correctly for percutaneous sampling of tissues. Frequently sonography with fine needle aspiration cytology or biopsy is the least expensive, safest and most direct route to a definitive diagnosis. Abscesses can be similarly diagnosed but with needles or catheters through which the pus can be drained.

The versatility and mobility of sonography has spawned other uses, particularly for the very ill and immobile, for intensive therapy units and for the operating theatre, as well in endosonography. The appointment of more skilled sonographers to the National Health Service could make a substantial contribution to cost-effective management of hospital services.

Just when contrast agents and angiography have become safe and are performed rapidly, they are being supplanted by scanning methods. They are now mainly used for interventional procedures or of pre-operative 'road maps' and may be required even less in the future as MRI angiography and Doppler techniques progress.

MRI will almost certainly extend its role beyond the central nervous system (CNS) should the equipment become more freely available, especially to orthopaedics. Until then plain films, sonography or CT will have to suffice. Even in the CNS there are conditions where CT is more diagnostic, as in showing calcification in cerebral cysticercosis. Then, too, in most cases CT produces results comparable to MRI apart from areas close to bone, structures at the base of the brain, in the posterior fossa and in the spinal cord.

Scintigraphy for pulmonary infarcts and bone metastases and in renal disease in children plays a prominent role and its scope has increased with new equipment and radionuclides. Radio-immunoscintigraphy in particular is likely to expand greatly not only in tumour diagnosis but also in metabolic and infective conditions. Whether the therapeutic implications will be realized is more problematic. The value of MRS and NM for metabolic studies in clinical practice is equally problematical, although the data from cerebral activity are extremely interesting.

While scanning has replaced many radiographic examinations, endoscopy has had a similar effect on barium meals and to a lesser extent on barium enemas. The combined visual/sonographic endoscope is likely to accelerate this process.

There is no doubt that over the last 2 decades medical imaging has changed the diagnostic process, but its influence on the outcome of disease other than infections is less certain and probably undefinable. Data concerning the comparative efficacy in terms of patient outcome for each of the imaging techniques would be of considerable interest and a great help in determining diagnostic strategies.

References

The radiology department

1. Cho, P.S., Huang, H.K., Tillisch, J. *et al.* Clinical evaluation of a radiologic picture archiving and communication for a coronary care unit. *Am J Roentgenol* 1988, **151**: 823–827.
2. Huang, H.K., Mankovich, N.J., Kangaroo, H. *et al.* Picture archiving and communication system for CT, MR and US. *Radiology* 1987, **169**(P): 279.
3. Ratib, O.M., Mankovich, N.J., Taira, R.K. *et al.* Integration of an imaging network into a clinical PACS. Proceedings of the SPIE, Medical Imaging II, Newport Beach, CA, 1988, **914**: 1379–1383.
4. Chan, K.K., Lou, S. & Huang, H.K. Full-frame transform compression of CT and MR images. *Radiology* 1989, **171**: 846–851.
5. Batnitzky, S., Rosenthal, S.J., Siegel, E.L. *et al.* Teleradiology: an assessment. *Radiology* 1990, **177**: 11–17.
6. Cox, G.G., Cook, L.T., McMillan, J.H. *et al.* Chest radiography: comparison of high resolution digital displays with conventional and digital film. *Radiology* 1990, **176**: 771–776.
7. Vlasbloem, H. & Kool, L.J.S. AMBER: a scanning multiple-beam equalization system for chest radiography. *Radiology* 1988, **169**: 29–34.
8. Kool, L.J.S., Busscher, D.L.T., Vlasbloem, H. *et al.*, Advanced multiple-beam equalization radiography in chest radiology: a simulated nodule detection study. *Radiology* 1988, **169**: 35–39.

Sonography

9. Holm, H.H., Als, O. & Gammelgaard, J. Percutaneous aspiration biopsy procedures under ultrasound visualization. In: *Clinics in Diagnostic Ultrasound. Vol. 1: Diagnostic Ultrasound in Gastrointestinal Disease*. Churchill Livingstone, New York, 1978, pp. 137–140.
10. Otto, R. & Deyle, P. Guided puncture under real-time sonographic control. *Radiology* 1980, **134**: 784–785.
11. McGahan, J.P. & Walter, J.P. Diagnostic percutaneous aspiration of the gall-bladder. *Radiology* 1985, **155**: 619–622.
12. Grant, E.G., Richardson, J.D., Smirniotopoulos, J.G. & Jacobs, N.M. Fine-needle biopsy directed by real-time sonography. Technique and accuracy. *Am J Roentgenol* 1983, **141**: 29–32.
13. Kuligowska, E., Connors, S.K. & Shapiro, J.H. Liver abscess: sonography in diagnosis and treatment. *Am J Roentgenol* 1982, **138**: 253–257.
14. Gersof, S.G., Johnson, W.C., Robbins, A.H. *et al.* Intrahepatic pyogenic abscesses: treatment by percutaneous drainage. *Am J Surg* 1985, **149**: 487–494.
15. Krook, P.M., Allen, F.H., Bush, W.H. *et al.* Comparison of real-time cholecystosonography and oral cholecystography. *Radiology* 1980, **135**: 145–148.
16. Dong, B. & Chan, M. Improved sonographic visualization of choledocholithiasis. *J Clin Ultrasound* 1987, **15**: 185–190.
17. Ralls, P.W., Colletti, P.M., Lapin, S.A. *et al.* Real-time sonography in suspected acute cholecystitis. *Radiology* 1985, **155**: 767–771.
18. Gelfand, D.W., Wolfman, N.T., Ott, D.J. *et al.* Cholecystography vs gallbladder sonography: a prospective blinded reappraisal. *Am J Roentgenol* 1988, **151**: 69–72.
19. Amberg, J.R. & Leopold, G.R. Is oral cholecystography still useful? (commentary). *Am J Roentgenol* 1988, **151**: 73–74.
20. Chan, S.L., Cooperberg, P.L., McLoughlin, M.G. & Ewart, B. Grey scale ultrasonography: a refined tool for differentiating renal mass lesions. *Canad Med Assoc J* 1980, **122**: 321–322.
21. Pollock, H.M., Banner, M.P., Arger, P.H. *et al.* The accuracy of grey scale ultrasonography in differentiating cystic renal neoplasms from benign renal cysts. *Radiology* 1982, **143**: 741–745.
22. Whalen, J.P. Radiology of the abdomen: impact of new imaging methods. *Am J Roentgenol* 1979, **133**: 585–618.
23. Lewis-Jones, H.G., Lamb, G.H.R. & Hughes, P.L. Can ultrasound replace the intravenous urogram in preliminary investigation of renal tract disease? A prospective study. *Br J Radiol* 1989, **26**: 977–980.
24. Charboneau, J.W., Hattery, R.R., Ernst, R.R. *et al.* Spectrum of sonographic findings in 125 renal masses other than benign simple cysts. *Am J Roentgenol* 1983, **140**: 87–94.
25. Lipscomb, D.J. & Flower, C.D.R. Ultrasound in the diagnosis and management of pleural disease. *Br J Dis Chest* 1980, **74**: 353–361.
26. Dorne, H.L. Differentiation of pulmonary parenchymal consolidation from pleural disease using the sonographic fluid bronchogram. *Radiology* 1986, **158**: 41–42.
27. Singh, S., Wann, L.S., Schuchard, G.H. *et al.* Right ventricular and right atrial collapse in patients with cardiac tamponade. A combined echocardiographic and haemodynamic study. *Circulation* 1984, **70**: 966–971.
28. Acquatella, H., Schiller, N.B., Piugbo, J.J. *et al.* Value of two-dimensional echocardiography in endomyocardial disease with and without eosinophilia. *Circulation* 1983, **67**: 1219–1226.
29. Gullace, G., Savoia, M.T., Ravizza, P. *et al.* Detection of atrial septal defect with left to right shunt by inferior vena cava contrast echocardiography. *Br Heart J* 1982, **47**: 445–453.
30. Weyman, A.E., Wann, L.S., Caldwell, R.L. *et al.* Negative contrast echocardiography: a new method for detecting left-to-right shunts. *Circulation* 1979, **59**: 498–505.
31. Meyers, D.G., McCall, D., Sears, T.D. *et al.* Duplex pulsed doppler echocardiography in mitral regurgitation. *J Clin Ultrasound* 1986, **14**: 117–121.
32. Sutherland, S.G. & Roelandt, J.R.T.C. Oesophageal echocardiography. *Br Heart J* 1988, **60**: 1–3.
33. Vilgrain, V., Mompoin, D., Palazzo, L. *et al.* Staging of oesophageal carcinoma: comparison of results with endoscopic sonography and CT. *Am J Roentgenol* 1990, **155**: 277–281.
34. Polensky, J., Ziegler, K., Samft, C. *et al.* Endoscopic ultrasonography in the diagnosis of benign and malignant lesions of the gastric wall. *Dtsch Med Wochenschr* 1988, **113**: 1263–1270.
35. Angelini, L., Bezzi, M., Tucci, G. *et al.* The ultrasonic detection of insulinomas during surgical exploration of the pancreas. *World J Surg* 1987, **11**: 642–647.
36. Barnett, E. & Morley, P. In: *Clinical Diagnostic Ultrasound*. Blackwell Scientific Publications, Oxford, London, 1985, chapters 28–32, pp. 465–531.
37. Thorsen, M.K., Lawson, T.L., Aimen, E.J. *et al.* Diagnosis of ectopic pregnancy: endovaginal vs transabdominal sonography. *Am J Roentgenol* 1990, **155**: 307–310.
38. Dillon, E.H., Feyoch, A.L. & Taylor, K.J.W. Pseudogestational sacs: doppler US differentiation from normal or abnormal intrauterine pregnancies. *Radiology* 1990, **176**: 359–364.
39. Bree, R.L., Edwards, M., Bohm-Valez, M. *et al.* Transvaginal sonography in the evaluation of early normal pregnancy: correlation with HCG level. *Am J Roentgenol* 1989, **153**: 75–79.
40. Wikland, M., Enk, L., Hammarberg, K. & Nilsson, L. Use of a vaginal transducer for oocyte retrieval in an IVF-ET program. *J Clin Ultrasound* 1987, **15**: 245–251.
41. Di Candio, G., Mosca, F., Campeteli, A. *et al.* Endosonographic staging of rectal carcinoma. *Gastrointest Radiol* 1987, **12**: 289–295.
42. Watanabe, H., Date, S., Ohe, H. *et al.* A survey of 3000 examinations by transrectal ultrasonotomography. *Prostate* 1980, **1**: 271–278.
43. Hamper, U.M., Sheth, S., Walsh, P.C. & Epstein, J.I. Bright echogenic foci in early prostatic carcinoma: sonographic and pathological correlation. *Radiology* 1990, **176**: 339–343.
44. McNeal, J.E. Normal anatomy of the prostate and changes in benign prostatic hypertrophy and carcinoma. *Seminars in Ultrasound, CT, and MR* 1988, **9**: 329–334.
45. Spamer, C., Brambs, H.-J., Koch, H.K. & Gerok, W. Benign circumscript lesions of the liver diagnosed by ultrasonically guided fine-needle biopsy. *J Clin Ultrasound* 1986, **14**: 83–88.
46. Braun, B. & Dormeyer, H.H. Ultrasonically guided fine-needle aspiration biopsy of hepatic and pancreatic space-occupying lesions and percutaneous abscess drainage. *Klin Wochenschr* 1981, **59**: 707–712.
47. Deyoe, L.A., Cronan, J.J., Lambiase, R.E. & Dorfman, G.S. Percutaneous drainage of renal and perirenal abscesses: results in 30 patients. *Am J Roentgenol* 1990, **155**: 81–83.
48. Farin, P.U., Jaroma, H., Harju, A. & Soimakallio, S. Shoulder impingement syndrome: sonographic evaluation. *Radiology* 1990, **176**: 845–849.
49. Bretzke, C.A., Crass, J.R., Craig, E.V. & Fineberg, S.B. Ultrasonography of the rotator cuff: normal and pathological anatomy. *Invest Radiol* 1985, **20**: 311–315.
50. Mitchell, D.G. Color doppler imaging: principles, limitations and artefacts. *Radiology* 1990, **177**: 1–10.
51. Rose, S.C., Zwiebel, W.J., Nelson, B.E. *et al.* Symptomatic lower extremity deep venous thrombosis: accuracy limitations and role of color duplex flow imaging in diagnosis. *Radiology* 1990, **175**: 639–644.
52. Vaccaro, J.P., Cronan, J.J. & Dorfman, G.S. Outcome analysis of patients with normal compression US examinations. *Radiology* 1990, **175**: 645–649.

53. Moriyasu, F., Ban, M., Nishida, O. *et al.* Clinical application of an ultrasonic duplex system in the quantitative measurement of portal blood flow. *J Clin Ultrasound* 1986, **14**: 579–588.
54. Yasuhara, K., Kimura, K., Ohto, M. *et al.* Pulsed doppler in the diagnosis of small tumours. *Br J Radiol* 1988, **?**: 898–902.
55. Lerner, R.M., Mevorach, R.A., Hulbert, W.C. & Rabinowitz, R. Color doppler US in the evaluation of acute scrotal disease. *Radiology* 1990, **176**: 355–358.
56. Rubin, J.M. & Dohrman, G.J. Efficacy of intraoperative ultrasound for evaluating intracranial masses. *Radiology* 1985, **157**: 509–511.
57. Rodiere, M. & Montoya, F. Ultrasound diagnosis and follow-up of brain haemorrhages in premature infants. *Ann Radiol* 1981, **25**: 72–80.

Computed tomography

58. Hounsfield, G.N. Design principles of the EMI scanner. In: Nicholson, J.P. (ed.) *Scientific Aids in Hospital Diagnosis*. Plenum Press, New York, 1976, pp. 119–130.
59. Kreel, L. The EMI body scanner: an interim clinical evaluation. *J Neuroradiology* 1976, **3**: 159–182.
60. Rumberger, J.A., Feiring, A.J., Lipton, M.J. *et al.* Use of ultrafast computed tomography to quantitate regional myocardial perfusion: a preliminary report. *J Am Coll Cardiol* 1987, **9**: 59–64.
61. Remy-Jardin, M., Beuscart, R., Sault, M.C. *et al.* Subpleural micronodules in diffuse infiltrative lung diseases: evaluation with thin-section CT scans. *Radiology* 1990, **177**: 133–139.
62. Isherwood, I., Forbes, W.St.C. & Griffin, J.F. CT scanning: the body. In: Sutton, D. (ed.) *A Text-book of Radiology and Imaging*. Churchill Livingstone, Edinburgh, 1987, pp. 1691–1738.
63. Sutton, D. & Moseley, J.F. Computed tomography: CNS. In: Sutton, D. (ed.) *A Text-book of Radiology and Imaging*. Churchill Livingstone, Edinburgh, 1987, pp. 1598–1653.
64. Ellert, J. & Kreel, L. The value of CT in malignant colonic tumors. *J Comput Tomogr* 1980, **4**: 225–240.
65. Bergin, C.J., Coblenz, C.L., Chiles, C. *et al.* Chronic lung diseases: specific diagnosis by using CT. *Am J Roentgen* 1989, **152**: 1183–1189.
66. Zerhouni, E. Computed tomography of the pulmonary parenchyma: an overview. *Chest* 1989, **95**: 901–907.
67. Schurawitzki, H., Stiglbauer, R., Graninger, W. *et al.* Interstitial lung disease in progressive systemic sclerosis: high-resolution CT versus radiography. *Radiology* 1990, **176**: 755–799.
68. Webb, W.R. High resolution CT of the lung parenchyma. *Radiol Clin N Am* 1989, **27**: 1085–1097.
69. Lipton, M.J. Quantitation of cardiac function by Cine-CT. *Radiol Clin N Am* 1985, **23**: 613–626.
70. Lipton, M.J., Higgins, C.B., Farmer, D. *et al.* Cardiac imaging with a high-speed Cine-CT scanner: preliminary results. *Radiology* 1984, **152**: 579–582.
71. Rich, S., Chomka, E.V., Stagl, R. *et al.* Determination of left ventricular fraction using ultra-fast computed tomography. *Am Heart J* 1986, **112**: 392–395.
72. Eldredge, W.J. & Flicker, S. Evaluation of congenital heart disease using Cine-CT. *Am J Cardiac Imaging* 1987, **1**: 38–50.
73. Pykett, I.L., Newhouse, J.H., Buonanno, F.S. *et al.* Principles of nuclear magnetic resonance imaging. *Radiology* 1982, **143**: 157.
74. Mitchell, M.R., Tarr, R.W., Conturo, T.E. *et al.* Spin echo technique selection: basic principles for choosing MRI pulse sequence timing intervals. *Radiographics* 1986, **6**: 245–254.
75. Bydder, G.M., Payne, J.A., Collins, A.G. *et al.* Clinical use of rapid T₂-weighted partial saturation sequences in MR imaging. *J Comp Asst Tomogr* 1987, **11**: 17–23.
76. Haase, A., Frahm, J., Matthaei, D. *et al.* FLASH imaging: rapid NMR imaging using low flip-angle pulses. *J Magn Reson* 1986, **67**: 258–266.
77. Hening, J., Nauerth, A. & Friedburg, H. RARE imaging: a fast imaging method for clinical MR. *Magn Reson Med* 1986, **3**: 823–833.
78. Bydder, G.M. & Young, I.R. MRI: clinical use of the inversion recovery sequence. *J Comp Asst Tomogr* 1985, **9**: 659–675.
79. Bydder, G.M. & Steiner, R.E. NMR imaging of the brain. *Neuroradiology* 1982, **23**: 147–157.
80. Brandt-Zawadzki, M., Norman, D., Newton, T.H. *et al.* Magnetic resonance of the brain: the optimal screening technique. *Radiology* 1984, **152**: 71–77.
81. Curati, W.L., Graif, M., Kingsley, D.P.E. *et al.* MRI in acoustic neuroma: a review of 35 patients. *Neuroradiology* 1986, **28**: 208–214.
82. Stadnik, T., Stevenaert, A., Beckers, A. *et al.* Pituitary microadenomas: diagnosis with two-and-three dimensional MR imaging at 1.5T before and after injection of gadolinium. *Radiology* 1990, **176**: 419–428.
83. Pomeranz, S.J. Magnetic resonance imaging of the spine. *NMR: Update Series* 1985, **10**: 1–?.
84. Modic, M.T., Masaryk, T., Paushter, D. Magnetic resonance imaging of the spine. *Radiol Clin N Am* 1986, **24**: 229–245.
85. Modic, M.T., Masaryk, T., Boumpfrey, F.L. *et al.* Lumbar herniated disc disease and canal stenosis: prospective evaluation by surface coil MR, CT and myelography. *AJNR* 1986, **7**: 709–717.
86. Flanders, A.E., Schaefer, D.M., Doan, H.T. *et al.* Acute cervical spine trauma: correlation of MR imaging findings with degree of neurologic deficit. *Radiology* 1990, **177**: 25–33.
87. Hackney, D.B. Denominators of spinal cord injury (editorial). *Radiology* 1990, **177**: 18–20.
88. Ricci, C., Cova, M., Kang, Y.S. *et al.* Normal age-related patterns of cellular and fatty bone marrow distribution in the axial skeleton: MR imaging study. *Radiology* 1990, **188**: 83–88.
89. Weinreb, J.C. MR imaging of bone marrow: a map could help (editorial). *Radiology* 1990, **177**: 23–24.
90. Reicher, M.A., Bassett, L.W. & Gold, R.H. High-resolution magnetic resonance imaging of the knee joint: pathologic correlations. *Am J Roentgen* 1985, **145**: 903–909.
91. Bluemm, R.G., Falke, T.H.M., Ziesdes des Plantes, B.G. *et al.* Early LEGG-Perthes disease (ischemic necrosis of the femoral head) demonstrated by magnetic resonance imaging. *Skel Radiol* 1985, **14**: 95–98.
92. Totty, W.G., Murphy, W.A., Ganz, W.I. *et al.* Magnetic resonance imaging of the normal and ischemic femoral head. *Am J Roentgen* 1984, **143**: 1273–1280.
93. Flannigan, B., Kursunoglu-Brahme, S., Snyder, S. *et al.* MR arthrography of the shoulder: comparison with conventional MR imaging. *Am J Roentgen* 1990, **155**: 829–832.
94. Laakman, R.W., Kaufman, B., Han, J.S. *et al.* MR imaging in patients with metallic implants. *Radiology* 1985, **157**: 711–714.
95. Sundaram, M. & McLeod, R.A. MR imaging of tumor and tumorlike lesions of bone and soft tissue. *Am J Roentgen* 1990, **155**: 817–825.

Magnetic resonance imaging

73. Kean, D. & Smith, M. *Magnetic Resonance Imaging*. William Heinemann Medical Books, London, 1986, pp. 50–69.
74. Kereiakes, J.G. Magnetic resonance imaging physics. In: Pomeranze, S.J. (ed.) *Craniospinal Magnetic Resonance Imaging*. W.B. Saunders, Philadelphia, 1989, pp. 1–15.
75. Heiken, J.P., Glazer, H.S., Lee, J.K.T. *et al.* *Manual of Clinical Magnetic Resonance Imaging*. Raven Press, New York, 1986.

99. Burbank, F., Parish, D. & Wexler, L. Echocardiographic-like angled views of the heart by MR imaging. *J Comp Assis Tomogr* 1988, **12**: 181–195.
100. Suzuki, J., Caputo, G.R., Kondo, C. & Higgins, C.B. Cine MR imaging of valvular heart disease: display and imaging parameters affect the size and the signal void caused by valvular regurgitation. *Am J Roentgen* 1990, **155**: 723–727.
101. McNamara, M.T., Higgins, C.B., Schechtman, N. *et al.* Detection and characterization of acute myocardial infarction in man with use of gated magnetic resonance. *Circulation* 1985, **71**: 717–724.
102. Higgins, C.B., Lanzer, P., Stark, D. *et al.* Imaging by nuclear magnetic resonance in patients with chronic ischemic heart disease. *Circulation* 1984, **69**: 523–531.
103. Brown, D.G., Riederer, S.J., Jack, C.R. *et al.* MR angiography with oblique gradient-recalled echo technique. *Radiology* 1990, **176**: 461–466.
104. Edelman, R.R., Mattle, H.P., Wallner, B. *et al.* Extracranial carotid arteries: evaluation with 'Black Blood' MR angiography. *Radiology* 1990, **177**: 45–50.
105. Kier, R., McCarthy, S.M., Scoutt, L.M. *et al.* Pelvic masses in pregnancy: MR imaging. *Radiology* 1990, **176**: 709–713.
117. Gjedde, A. & Wong, D.F. Positron tomographic quantitation of neuroreceptors in human brain *in vivo* – with special reference to the D-2 dopamine receptors in caudate nucleus. *Neurosurg Rev* 1987, **10**: 9–17.
118. Early, T.S., Reiman, E.M., Raichle, M.E. *et al.* Left globus pallidus abnormality in never-medicated patients with schizophrenia. *Proc Natl Acad Sci USA* 1987, **84**: 561–563.
119. Levin, D.N., Hu, X., Tan, K.K. *et al.* Integrated 3-D display of MR, CT, and PET images of the brain. *Proc Natl Comput Graphics Assoc* 1989, **1**: 179–186.
120. Berger, H., Lahiri, A., Leppo, J. *et al.* Antimyosin imaging in patients with ischemic chest pain: initial results of phase III multicenter trial. *J Nucl Med* 1988, **29**: 805–806 (abstract).
121. Larson, S.M. Lymphoma, melanoma, colon cancer: diagnosis and treatment with radiolabeled monoclonal antibodies. The 1986 Eugene P. Pendergrass New Horizons Lecture. *Radiology* 1987, **165**: 297–304.
122. Serafini, A.N., Garty, I., Jabier, A.M. *et al.* Monoclonal antibody imaging, clinical and technical perspectives. *Antibody, Immunoconjugates and Radiopharmaceuticals* 1989, **2**: 225–234.
123. Hawkins, M.B., Lavender, J.P. & Pepys, M.B. Evaluation of systemic amyloidosis by scintigraphy with ¹²⁵I-labeled serum amyloid P component. *N Engl J Med* 1990, **323**: 508–513.

Magnetic resonance spectroscopy

106. Matson, G.B. & Weiner, M.W. MR spectroscopy *in vivo*: principles, animal studies and clinical applications. In: *Magnetic Resonance Imaging*, Stark, D.D. & Bradley, W.G. (eds). C.V. Mosby, St Louis, 1988, pp. 201–228.
107. van der Knaap, M.S., van der Grond, J., van Rijen, P.C. *et al.* Age-dependent changes in localized proton and phosphorus MR spectroscopy of the brain. *Radiology* 1990, **176**: 509–515.
108. Ross, B.D., Tropp, J., Derby, K.A. *et al.* Metabolic response of glioblastoma to adoptive immunotherapy: detection by phosphorus MR spectroscopy. *J Comp Assis Tomogr* 1989, **13**: 189–193.
109. Brown, J.J., Mirowitz, S.A., Ssandstrom, J.C. & Perman, W.H. MR spectroscopy of the heart. *Am J Roentgen* 1990, **155**: 1–11.
110. Luyten, P.R., Marien, A.J.H., Heindel, W. *et al.* Metabolic imaging of patients with intracranial tumours: H-1 MR spectroscopic imaging and PET. *Radiology* 1990, **176**: 791–799.
111. Oberhaensli, R.D., Hilton-Jones, D., Bore, P.J. *et al.* Biochemical investigation of human tumours *in vivo* with phosphorous-31 magnetic resonance: spectroscopy. *Lancet*, **ii**: 8–11.
112. Fossell, E.T., Carr, J.M. & McDonagh, J. Detection of malignant tumours: water-suppressed proton nuclear magnetic resonance spectroscopy of blood samples. *N Engl J Med* 1986, **315**: 1369–1376.

Nuclear medicine

113. Townsend, C.E., Costa, D.C., Jarritt, P.H. *et al.* Evaluation of a new three-detector gamma camera (IGE NEUROCAM) in a clinical environment. *Eur J Nucl Med* 1990, **16**: 560–564.
114. Ter-Pogossian, M.M. Physical aspects of emission computed tomography. In: Newton, T.H. & Potts, S.G. (eds). *Radiology of the Skull and Brain: Technical Aspects of Computed Tomography*. Mosby, St Louis, 1981, pp. 372–488.
115. Greitz, T., Ingvar, D. & Widén, L. *Positron Emission Tomography*. Raven Press, New York, 1985.
116. Valk, P.E., Jagust, W.J., Derenzo, S.E. *et al.* Clinical evaluation of a high-resolution (2.6-mm) positron emission tomograph. *Radiology* 1990, **176**: 783–790.

Digital subtraction angiography

124. Aaron, J.O., Hesselink, J.R., Oot, R. *et al.* Complications of intravenous DSA performed for carotid artery disease: a prospective study. *Radiology* 1984, **153**: 875–878.
125. de Lihtite, M.D., Marc-Vergnas, J.P., Rascol, A.M. *et al.* Intravenous angiography of the extracranial carotid arteries. *Radiology* 1980, **137**: 705–711.
126. Thornbury, J.R., Stanley, J.C. & Fryback, D.G. Optimising work-up of adult hypertensive patients for renal artery stenosis. *Radiol Clin N Am* 1984, **22**: 333–339.

Non-ionic contrast medium

127. McClennan, B.L. Ionic and nonionic iodinated contrast media: evolution and strategies for use. Preston M Hickey Memorial Lecture. *Am J Roentgen* 1990, **155**: 225–233.
128. Palmer, F.J. The RACR survey of intravenous contrast media reactions: final report. *Australas Radiol* 1988, **61**: 1334–1337.

Radiological screening programmes

129. Shirakabe, H., Nishizawa, M., Maruyama, M. & Kobayashi, S. Chapt. 1. In: *Atlas of X-ray Diagnosis of Early Gastric Cancer*, 2nd edition. Igaku-Shoin Ltd, Tokyo, New York, 1982, pp. 1–18.
130. Baker, L.H. Breast cancer detection demonstration project: 5 years summary report. *CA* 1982, **32**: 196–225.
131. Beahrs, O.H., Shapiro, S., Smart, C. *et al.* Report of the working group to review the National Cancer Institute – American Cancer Society Breast Cancer Detection Demonstration Projects. *J Natl Cancer Inst* 1979, **62**: 639–698.
132. Collette, H.J.A., Rombach, J.J., Dey, N.E. *et al.* Evaluation of screening for breast cancer in a non-randomized study (the DOM Project) by means of a case-control study. *Lancet* 1984, **i**: 1224–1226.
133. Skrabanek, P. False premises and false promises of breast cancer screening. *Lancet* 1985, **ii**: 316–320.