SIR PETER MANSFIELD
9 October 1933 — 8 February 2017
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Elected FRS 1987

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Peter Mansfield’s rise from humble origins to founding father of magnetic resonance imaging (MRI) is an inspirational and remarkable story. His first scientific contributions were in the field of solid state nuclear magnetic resonance (NMR), and it was whilst trying to develop an NMR version of X-ray crystallography that he developed the underpinning methodology for MRI. At that time (the early 1970s) NMR was an analytical tool, ubiquitous in chemistry departments. For most of those working in the field, there was no hint that it could be developed into a diagnostic imaging technique that would reveal internal anatomy in unprecedented detail. Yet that was what happened in the space of just a few years. The first MRI scans were slow, and Peter was driven to speed them up, making physiological and later functional brain imaging studies possible. The technical challenges were many, and eschewed by healthcare equipment providers, but Peter persisted and his brainchild, echo-planar imaging, came to dominate the high speed MRI field. Peter was a gifted physicist and archetypal inventor who devoted his life to the development of a technique that has saved millions of lives. In 2003, he shared the Nobel Prize for Physiology or Medicine, in recognition of his achievement.

EARLY YEARS

Peter Mansfield was born in Lambeth on 9 October 1933 to Sidney George Mansfield, a gas fitter, and Rose Lillian Mansfield (née Turner). The youngest of three brothers, Peter grew up in Camberwell but spent the war years as an evacuee in Babbacombe, Devon. He returned to

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London briefly in 1943, when it seemed that the bombing raids had subsided, in time to witness the arrival of the V1 rockets, and the first of the V2s. Far from the terrifying experience one might expect it to have been for a young boy, Peter was fascinated, and it was to lead him to a career in science.

His disrupted education led to his failing his 11 plus exam, and he left school aged 15 with no formal qualifications. When asked about a career in science, his careers master suggested he ‘should consider something less ambitious’, and so in 1949 he went into the printing profession, first at Ede and Fisher as an apprentice in the bookbinding department, then at Strakers as an apprentice compositor. Whilst there he read an article in the *Children’s Mirror* about the experiences of a boy working at the Rocket Propulsion Department in Westcott. He wrote to the editor to ask how he might go about securing a similar position and was directed to the Ministry of Supply, who, following interview, offered him a job in the Solid Propellant Division at Westcott in 1952.

Peter had been going to evening classes five nights a week at Borough Polytechnic, from where he obtained his General Certificate of Education. He enrolled at Oxford Polytechnic during his military service to study for A Levels in physics and mathematics, which he obtained on his return to the Rocket Propulsion Department. With the encouragement of the staff there, he applied for admission to the honours course in physics at Queen Mary College (now Queen Mary University of London), which he commenced in October 1956.

**University training**

Peter excelled as an undergraduate and he found time to initiate a new society, The Interplanetary Society, whose journal, *The Rocket*, he edited. His first encounter with nuclear magnetic resonance (NMR) came in his final year project, which was to develop an Earth’s field proton magnetometer, using transistors rather than valves. He used a water sample to produce an audio free induction decay (FID) at 2 kHz—a long ‘ping’ in regions of uniform field and a short ‘pip’ as he moved across the front lawn of the College over buried ferrous objects (figure 1). His project supervisor was Jack Powles, and he was sufficiently impressed to publish a short article on it in the *New Scientist*. Having graduated with a first class degree, Peter elected to continue as his PhD student. His project this time was to develop a spectrometer for solid state NMR. He had a 0.5 T Mullard magnet, but otherwise started from scratch, using methods based on radar technology to generate the short radiofrequency (RF) pulses (<1 μs) required to excite the very broad solid resonances (2)*.

In liquid state NMR, Erwin Hahn (ForMemRS 2000; Hahn 1950) had shown that a second RF pulse could elicit an echo. These Hahn (spin) echoes generated much interest and later came to play a prominent role in magnetic resonance imaging (MRI). They arose because the coherent dephasing of spins in inhomogeneous magnetic fields was reversed by the second pulse. However, the incoherent decay due to random interactions between spins, characterized by the spin–spin relaxation time $T_2$, could not be refocused, limiting the length of the echo time. In solids, $T_2$ values are often very short, typically microseconds, and so, it was reasoned, echoes on the time scale observed in liquids should not occur. But that is precisely what Peter observed; his first paper (1), on solid echoes, was published in volume 2 of *Physics Letters*.

* Numbers in this form refer to the bibliography at the end of the text.
After his PhD, Peter went to work in Charlie Slichter’s laboratory at the University of Urbana in Champaign, Illinois. He travelled to the United States on the Queen Mary, arriving as the Cuban Missile Crisis was unfolding. The two postdoctoral years he spent there were happy ones, but his work on the NMR of metals did not prove productive and in 1964 he returned to the UK to take up the offer of a lectureship from Raymond Andrew (FRS 1984), Peter’s PhD examiner and the newly appointed head of physics at the University of Nottingham.

**SOLID state NMR**

With a start-up grant from the Science Research Council (SRC), Peter purchased a Varian magnet and power supply, and, with the assistance of his PhD student, Donald Ware, he
continued his work on solid echoes. He found that by applying a train of intense RF pulses to his chosen test sample—a single crystal of calcium fluoride—he could sustain a FID for more than a second, even though the $T_2$ of the crystal was only about 40 $\mu$s. This was published in 1966 (3), just at the time John Waugh at MIT published his own work on multiple pulse NMR in *Physics Review Letters* (Ostroff & Waugh 1966). This led to an intense rivalry between the two groups, sometimes bitter, but always scientifically productive. Scientific competition came to be a feature of working in the Mansfield group!

The removal of the dipolar interaction between spins, leading to the prolongation of the FID, began to be understood and described using average Hamiltonian theory. The ability to reverse the sign of the average dipolar Hamiltonian using RF pulses can be viewed as equivalent to time reversal, and led to a series of interesting studies by Waugh and his colleagues (Rhim et al. 1971). The solid echoes they generated came to be known as ‘magic echoes’.

Solid state NMR was certainly centre stage, at least in the NMR world, at the start of the 1970s. Multiple pulse sequences were designed to remove successively higher orders in the dipolar expansion. Waugh and his colleagues Huber and Haeberlen produced the four-pulse WAHUHA sequence (Waugh et al. 1968); Peter devised an eight-pulse line-narrowing sequence based on reflection symmetry (4). This was later ‘rediscovered’ by Rhim and his colleagues Elleman and Vaughan (Rhim et al. 1973), who christened it the REV8 sequence. Once it became clear that it was identical to Peter’s reflection cycle, it was renamed the MREV8 sequence. With research students Ken Richards and Dennis Stalker and postdoctoral fellow, Allen Garroway from Cornell, Peter designed ever more sophisticated multipulse sequences based on symmetry arguments (8, 10). His partially permuted 16-pulse sequence was particularly efficacious. The implementation of such sequences was greatly facilitated by the use of a computer-controlled spectrometer, the first of its kind. The computer in question, purchased with the aid of a substantial SRC grant, was a Honeywell 316 (see figure 2) equipped with 4 K of magnetic memory. (An additional 4 K was later purchased at a cost of £4K!) This was a synchronous machine, and the RF pulses were triggered as pulse codes were clocked into its register, which was (literally) hard-wired to the pulse generators.

The dipolar interaction between spins contains a $(3\cos^2\varphi - 1)$ term, where $\varphi$ is the angle between the vector joining the spins and the magnetic field. It is zero at the ‘magic angle’ and if the sample is spun rapidly about an axis inclined to the magnetic field at this angle,
the dipolar interaction is removed. This alternative line-narrowing method was first developed by Raymond Andrew and colleagues (Andrew et al. 1958) and came to be known as magic angle sample spinning (MAS). Following Peter’s move to Nottingham, Andrew continued to develop MAS, and another scientific rivalry developed between him and Peter.

At that time, the principal interest in removing the dipolar interaction was to reveal the smaller chemical shift interactions. In liquids, motional averaging results in a single isotropic chemical shift but in solids the full tensor remains, and this provides information on molecular and crystal structures. The multipulse techniques retain this information, whereas MAS leaves just the isotropic shift. Eventually, however, scientists lost interest in chemical shift anisotropy, and MAS techniques now dominate the field of solid state NMR.

Peter was ‘working through’ the fluorinated materials he had available, and it was at this point (October 1974) that I joined his group. I designed and implemented a fully permuted cycle (26 RF pulses per sample point) and was asked to explore some amphiphilic liquid crystals supplied to us by Gordon Tiddy at Unilever. I found I could orient the liquid crystals in the magnetic field and perform rotation studies to determine the anisotropic chemical shift components (figure 3) in lamellar (15) and complex hexagonal phases (17).

**Development of MRI**

Line-narrowing methods had reached a developmental zenith by the early 1970s (5), and Peter was thinking about what to do next with the computer-controlled spectrometer he had developed. A ‘tea room’ discussion with Peter Grannell and Allen Garroway in the early summer of 1972 led to the idea that magnetic field gradients could be used to achieve spatial
resolution and that an NMR version of X-ray diffraction for the determination of crystal structures might be possible. Shortly afterwards, Peter left with his young family to spend a sabbatical year at the Max Planck Institut für Medizinische Forschung in Heidelberg, where he helped Ulrich Haeberlen to improve the stability of his solid state NMR apparatus, which was being used for studies of chemical shift anisotropy (Haeberlen 1976). Peter Grannell was left to develop a suitable gradient coil, and discussion continued through the frequent exchange of handwritten letters. Gradients of sufficient strength could not be generated to achieve the atomic resolution Peter hoped for, and so a model system based on layers of camphor was chosen. A multipulse line-narrowing sequence was applied, and, in the absence of any applied gradient, a single resonance was observed. However, when a gradient was applied normal to the planes, each layer of camphor resonated at a different frequency and an interference/diffraction pattern was observed in the FID. On Fourier transformation, this yielded a separate resonance for each camphor layer (figure 4). Peter presented these results at the first Specialized Colloque Ampere, in Krakow in August 1973 (6) and in a field-defining paper in the Journal of Physics C (7).

In Krakow, John Waugh drew Peter’s attention to a recent paper in Nature by Paul Lauterbur (Lauterbur 1973), with whom Peter would share a Nobel Prize for the development of MRI. Paul had developed a method of imaging by NMR in which spectra were recorded in field gradients of different orientation, and these projections were then combined (reconstructed) to generate an image. He presented his work at a meeting of the International Society for Magnetic Resonance in Bombay, early in 1974. It was attended by Bill Moore, Waldo Hinshaw and Bill Derbyshire, who, though excited, felt there was a better way to go about it. Their discussions led to the development of the sensitive point (and later sensitive line) technique based on the use of oscillating gradients to blur the information, other than
that coming from the sensitive region. The method was patented, and the first papers appeared (Hinshaw 1974, 1976). The race was on!

The first imaging studies were two-dimensional and either did not define the slice from which the image was generated or simply relied on the physical extent of the receiver coil to do so. Something better was required—and Peter, together with Allen Garroway and Peter Grannell, had been thinking about it. They realized that application of a magnetic field gradient during the application of a frequency selective pulse would limit excitation to a region in which the resonant frequency lay within the bandwidth of the pulse. A number of possibilities existed, including saturation of all spins lying outside the required region, followed by excitation of those remaining, or direct excitation of the required spins. A patent covering these approaches, and including provision for excitation of planes of arbitrary orientation, was taken out—a propitious decision given that every commercial system would later make use of selective pulses. The work was subsequently published in the *Journal of Physics C* (9). The concept of slice selection was not universally accepted, and in 1977 David Hoult published a paper entitled: ‘Zeugmatography: a criticism of the concept of a selective pulse in the presence of a field gradient’ (Hoult 1977). Peter, who had received a pre-print of the article, was incensed and published a robust response (16), for which I developed the theoretical analysis. From my perspective, this was a ‘healthy’ exchange of scientific views and it led to a proper appreciation of the need to rephase the selected spins through a reversal of the applied gradient. As a consequence, David and I developed a mutual respect and became lifelong friends; Peter was less forgiving!

Peter had soon realized that imaging solid samples using line-narrowing sequences was challenging; biological samples that, from an NMR standpoint, behaved as liquids were much more straightforward. He settled on a line-scanning technique (11, 12) and, for suitable candidates to image, scoured his garden—the stems of lupins—and his local greengrocers—okra seed pods (see figure 5). The spectrometer developed for solid state NMR was adapted; the variable resistors controlling the current through the gradient coils are at the bottom of the rack to the right of the Varian magnet in figure 2. A flood of papers appeared over the next few years, but they failed to impress the SRC. What changed things was the publication in the *British Journal of Radiology* of the first image to display live human anatomy—the finger of his PhD student, Andrew Maudsley (14).

Figure 5. NMR line-scan images of an okra seed pod (a) and human finger (b). (Image (a) is from the author’s collection and (b) is from the University of Nottingham, Manuscripts and Special Collections (PPM/15/68/3).) (Online version in colour.)
Peter was invited to a meeting, organized by the Medical Research Council (MRC) and chaired by Sir Rex Richards FRS, to discuss the development of MRI. He went armed with copies of colour coded images, which he had persuaded the company EMI to generate for him from data stored on paper tape (the main storage medium in use at that time!). (Peter had become a consultant for EMI following a meeting at their Central Research Laboratories in Hayes with Godfrey Hounsfield (FRS 1975), joint winner of the 1979 Nobel Prize for Physiology or Medicine for the development of X-ray computerized tomography.) Peter clearly made a powerful impression: not only did the MRC invite him to submit a grant application, which it duly awarded in 1975, but Rex asked whether he could propose him for Fellowship of the Royal Society, to which he was elected in 1987.

The MRC grant was to develop a whole-body MRI system—a massive increase in scale on what had been achieved, and a genuine ‘leap of faith’. The magnet, a 0.1 T four-coil electromagnet, was designed and built by Oxford Instruments. It was delivered on the last working day before Christmas of 1977. To achieve a uniform field, the magnet was ‘shimmed’ by re-positioning its four coils—my first practical contribution to MRI! By Easter of the following year, line-scanning images were being obtained from cadaver specimens supplied by the professor of human morphology at the newly opened Queens Medical Centre, but Peter was eager to have a live image and volunteered himself (figure 6). An abdominal image was recorded the evening before he and I left for the Experimental NMR Conference in Blacksburg, Virginia, in April 1978 (18). The film, with the images photographed from a black and white display monitor, was in my camera and was processed the day before the start of the meeting and Peter’s presentation. At the time, almost nothing was known about the safety of MRI. Indeed, Tom Budinger had recently sent round a note to laboratories he felt might be about to undertake human MRI studies in which he suggested that switching gradient fields could induce a cardiac arrest. We disagreed with his analysis. Nevertheless, Peter had ensured his will was up-to-date, and his wife was present at that first scan. It made a lasting impression, and Peter was not quick to volunteer on future occasions! Future generations have been able to appreciate the drama through a contemporary Tomorrows World TV report first broadcast by the BBC on 19 October 1978.

In the months following that first scan, studies were undertaken of different tissues, including a carcinoma-bearing mastectomy specimen—the first MRI of a breast tumour (19).
The development of MRI was at its most intense: Hinshaw and colleagues published an article in *Nature* (Hinshaw et al. 1977) showing images of the human wrist, and, on the front cover, a lemon in hitherto unsurpassed detail; the group in Aberdeen published the first clinical studies on cancer patients (Smith et al. 1981); the Hammersmith team published its work on multiple sclerosis (Young et al. 1981). Peter was asked by his old adversary, John Waugh, the editor of *Advances in Magnetic Resonance*, to contribute a review article on MRI. He enlisted my help and, over the course of a year, the article grew into a book (21) that not only described what had been achieved, but set out our thoughts on what might be possible in the future. It became a guiding reference for the early pioneers of MRI. By the first years of the 1980s, it was clear that MRI would come to play a significant role in medical diagnosis, and the major healthcare equipment providers committed to its commercial development. Peter had a choice to make: compete with industry on image quality, or focus on his passion for high speed imaging. He chose the latter, and again it proved prophetic.

**Echo-planar imaging**

Images were slow to acquire, either because they had to be gathered point by point or line by line, or because multiple projections or phase-encoding steps needed to be obtained before reconstruction could begin. From the outset, Peter wanted to image faster in order ‘freeze’ physiological movement—the beating heart, peristalsis or a fetus *in utero*. He was using arrays of test tubes held in a matrix as phantoms with which to test and refine imaging methods. He reasoned that, although spectra acquired in gradients of general orientation would yield projections in which signal from different tubes overlapped, special orientations could be picked for which there was no overlap, and effectively a complete image could be obtained from a single projection. This depended on having a discrete object—a matrix of small test tubes for example—so the problem of imaging in a single step could be reduced to discretizing the spin system. How could it be done? The answer came to him whilst waiting for a red light to change as he was driving home for lunch with his wife. If the NMR signal was recalled as a series of spin echoes by periodically reversing the applied gradient, then the frequencies describing that echo train would be multiples of the echo frequency—echo-planar imaging (EPI) was born—an incredible achievement in 1977 (13).

Peter was fortunate to have two excellent PhD students in his lab at that time: Richard Rzedzian and Roger Ordidge. They quickly realized that alternate echoes needed to be reversed—because they corresponded to traversal of *k*-space in opposite directions—and, with further improvements, they developed EPI into a practically useful imaging method. Roger developed a small gradient system and receiver coil for use in the 0.1 T whole-body magnet and used it to obtain images of peppers, the human hand and, most impressively, an EPI movie of a rabbit. This he showed at a meeting on NMR imaging held at the Bowman Gray School of Medicine to great acclaim (20). Each $32 \times 32$ pixel image was acquired in 32 ms, enabling the rabbit cardiac cycle to be represented over six frames—a spectacular demonstration of the potential of EPI. The focus for the next few years remained on cardiac imaging—of piglets (22) and, with Alan Chrispin, of young children with high respiratory and heart rates (23). The images were of sufficient quality that it proved possible to demonstrate structural abnormalities in the connection of the heart to the great vessels (27) or in cyanotic congenital heart disease (28). It was soon possible to extend the cardiac movie studies to adults...
and to collect the data from a single cardiac cycle (29); investigation of cardiac arrhythmias was now feasible.

In his original paper on EPI, Peter had discussed the possible extension to three dimensions—echo-volumar imaging, or EVI. The first steps were taken at 0.1 T (35), but full exploitation would await the introduction of higher field strengths. By the middle 1980s, Peter was being courted by several American universities and by the University of Oxford, where it was proposed to use a charitable fund set up by Sir Martin Wood (FRS 1987), founder of Oxford Instruments, to enable him to join George Radda FRS in a new facility that would embrace both MRI and MRS. In the event, the discussions coincided with a substantial grant to Peter from the Department of Health to purchase a 0.5 T superconducting magnet and with the first royalty payments to the National Research and Development Council from General Electric and Technicare. Peter elected to remain in Nottingham to develop EPI at higher field strength.

A major obstacle to the successful implementation of EPI is the induction by the rapidly switched field gradients of eddy currents in surrounding metallic structures, particularly the dewars of early superconducting magnets. These eddy currents introduce additional time-varying field gradients that distort the images. The gradient coils fit within the bore of the magnet, and Peter realized that the solution was to shield the bore from the effects of these coils by adding an outer set of screening coils. Together with his research student Barry Chapman, he patented and then published the idea of active magnetic screening (26). The basic concept was refined by another of Peter’s PhD students, Robert (Bob) Turner (Turner 1986), working with a theoretician Roger Bowley (Turner & Bowley 1986). Together they developed the ‘target field approach’, in which the desired field profile is specified and the current distribution required to generate it determined. This was incorporated into Peter’s
patent application and it became the chosen tool for gradient design both in the Mansfield lab (43) and in the healthcare industry (see figure 7).

As well as inducing troublesome eddy currents, fast gradient switching placed high demands on the audio amplifiers used to drive the gradient coils. Peter realized that this could be alleviated by using sinusoidal rather than square wave switching. This, however, required non-linear sampling of the echo train—something he was aware of from the outset, as evident from the pages in his laboratory notebook dated 21 August 1978 (figure 8), but did not refer to in publications until much later. Peter realized that a particularly efficient way to generate sinusoidal gradients was to make the gradient coils part of a resonant circuit, so that the energy required could be stored in parallel capacitors rather than supplied anew from the audio amplifiers (46). He later extended the idea to the generation of trapezoidal gradient waveforms (52).

An additional problem with rapid gradient switching is that it induces currents in the body that could lead to cardiac arrest (as contemplated by Peter prior to his first scan!) but more usually manifests as peripheral nerve stimulation (because it is at the extremities that the largest $\frac{dB}{dt}$ usually occurs). Peter studied the frequency dependence of these effects and attempted to mitigate them by controlling the spatial distribution of the electric fields generated by the gradient coils (64).
Clinical applications of EPI

Peter believed in building his own equipment; he had done so himself as a PhD student and postdoctoral fellow. Terry Baines, an electrical engineer, had helped him build his first computer-controlled spectrometer; for the development of the 0.5 T scanner, he was joined by two other excellent electrical engineers, Ron Coxon and later, Paul Glover. Improvements were made to EPI methodology (30) and ‘snap-shot’ images demonstrated in the head (31) and body (37).

The main drive was to freeze physiological motion. It had been well-demonstrated in cardiac studies at 0.1 T, but conventional MRI sequences were able to use ECG gating to obtain very high resolution images with which EPI, at the time, could not compete. However, other types of physiological movement were not periodic, and speed was the only option. Peter was joined by a young German medic, Michael Stehling, who came with a mission to drive the clinical application of EPI. He also sought to stimulate its wider adoption by the MRI community, and his 1991 paper in Science (47) certainly drew attention to its possibilities. The movie images of the gastro-intestinal tract generated on the new 0.5 T scanner had field-defining impact (36), and such studies remain a focus of clinical research in multiple centres, including Nottingham.

The other clinical target for the 0.5 T system was the assessment of the fetus in utero in abnormal pregnancy (41). With the arrival in Nottingham of Penny Gowland, intrauterine growth retardation became a primary focus, with methods developed for the accurate assessment of fetal weight (48) and the volumes of fetal organs (54). As the quality of EPI improved, Brian Worthington (FRS 1998) and Peter began to investigate neurological applications (42). They used it in the first dynamic studies of contrast enhancement in brain tumours (44), a technique that would later have important impact on tumour diagnosis and staging.

In addition to using EPI to study dynamic processes, Peter had always been conscious that conventional MRI was a comparatively slow technique, and he wanted to speed up diagnosis. As a demonstration for visiting parties, he would ‘slice up’ a human volunteer as they were pushed rapidly through the bore of the scanner. No one failed to be impressed! Peter planned to go even faster with whole-body EVI (57). If the imaging was to be ultra-fast, so too should be the assessment, and, if it were to be automated, it would be useful to base it on a specific parameter. The spin lattice relaxation time ($T_1$) was a good candidate, and Peter refined techniques to generate $T_1$ maps using EPI (40). He was also conscious that whole-body EPI had limited spatial resolution. To compensate, he developed a technique he called zonally magnified EPI, in which the image matrix covered a selected local region at higher spatial resolution (32).

EPI at higher fields

In 1991 Peter’s research lab moved to a new purpose-built site that later became known as the Sir Peter Mansfield Imaging Centre. It took delivery of the first 3 T whole-body magnet from Oxford Magnet Technology, and, continuing the tradition of in-house development, work began to build a dedicated high field imaging system based on EPI. The MRI field had briefly flirted with 4 T systems, but they had not proved successful and the major instrument
companies abandoned their high field programmes. This changed with the development of functional MRI (fMRI) (Belliveau et al. 1991). This was the tool neuroscientists had been waiting for—a non-invasive way with which to map brain function.

The first EPI images from the 3 T MRI system were published in 1994 (50), with the first 3 T fMRI study following shortly thereafter (53). This triggered a major new research initiative at Nottingham, and it became the focus for high (3 T) and later ultra-high field- (7 T) studies. For fMRI to work well, it was essential to image fast—and EPI was soon adopted as the standard imaging protocol. More than two decades after it was first proposed it entered widespread use, and system manufacturers had to offer EPI capability. Imaging a slice at a time, even rapidly using EPI, meant that activity in different slices would be time shifted and needed correction. Peter, of course, wanted to go faster, and in 1995 he published the first fMRI study at 3 T to use EVI (56).

**Other applications of MRI**

Whilst the main effort in the academic and commercial development of MRI was to improve structural imaging for clinical application, other possibilities were also envisaged from the outset (see discussions in Mansfield & Morris (21)).

In Oxford, George Radda and colleagues had developed and demonstrated the value of $^{31}$P MRS for studies of bioenergetic metabolism (Ackerman et al. 1980), and at Yale, Bob Shulman was using $^{13}$C MRS to investigate glycogen storage and metabolism in diabetes (Shulman et al. 1990). This exciting work made use of surface coils to acquire NMR spectroscopic (chemical shift) information from the underlying tissue. Fourier imaging methods were modified to enable chemical shift imaging (CSI) over larger volumes (Maudsley et al. 1983), but acquisition times were, and continue to be, very long (typically several tens of minutes). Peter as usual wanted to go faster. He published a modification of EPI (24), echo-planar spin mapping (EPSM), that retained most of the inherent speed of the parent technique, together with a hybrid method, projection reconstruction echo-planar imaging (PREP), that used EPI to acquire 1D projections of spectroscopic images that could subsequently be reconstructed. These methods were analysed theoretically (25) and demonstrated practically (33). Later, another hybrid method, phase-encoded echo-planar imaging (PEEP), was published (34). Now better known as echo-planar spectroscopic imaging (EPSI), this method is still in widespread use.

Field gradients had been used with conventional NMR sequences to investigate diffusion and flow before the advent of MRI. The ability to image these processes paid huge dividends. Peter naturally wanted to use EPI for this purpose, and he developed real-time flow measurement (39). He realized that it was possible to measure not only flow velocity but also acceleration and higher order flow parameters. He applied his new techniques to a variety of porous media (45), finally focusing on core samples of oil-bearing rocks (60). He developed theoretical models to describe the flow properties (58, 59), and continued his interest in this work well into his retirement. In fact, his last ever PhD student, Martin Bencsik, worked in this area (61) and continued with it when he moved to set up his own research group at Nottingham Trent University.

One of the questions most often asked about MRI is: what is the resolution limit? This was analysed in Mansfield & Morris (21), where different imaging regimes were explored,
including NMR microscopy in which the smaller number of spins contributing signal to each voxel could in part be compensated through the use of higher field strength magnets. A limiting factor turns out to be signal loss due to diffusion in the very high field gradients required (63). With Richard Bowtell, Peter constructed a microscope based on an Oxford Instruments 11.7 T vertical bore magnet, of the type normally supplied for high resolution NMR. For a time this instrument held the resolution record for MRI. Images at cellular resolution were shown at a meeting of the Royal Society organized by Peter (38). Resolution is improved if the receiver coil fits tightly round the sample (a high filling factor in the parlance of traditional NMR spectroscopy). With Paul Glover, Peter designed a microscope slide that incorporated a micro-coil to achieve this aim (49).

**Final contributions**

Peter decided to take early retirement in 1993 (see figure 9). This, of course, did not bring to an end his contribution to MRI. When members of the public talked to him about his role in its development, they were always duly reverential but invariably asked why he couldn’t do something about the noise—and this was his main occupation in retirement.

The noise is generated by the gradient coils: their windings carry large currents and are subject to substantial Lorentz forces in the high magnetic fields of MRI systems. This force varies as the gradients are switched, producing sounds that are characteristic of the particular gradient pulse sequence. For EPI, the switched gradient generates a distinct audio ‘beep’, which, if not attenuated, can exceed the threshold for damage to the auditory system. The best way to tackle a problem is usually at source: Peter explored methods to limit the forces acting on gradient coil formers (51) and designed gradient coils for which the Lorentz forces were
balanced (55). This led to a significant reduction of acoustic noise, but did not fully solve the problem. He looked in more detail at the noise-generating mechanisms and realized that it was the alternate compression and expansion of the formers on which the coils were wound that was generating the noise. In essence it was the return paths for the wires in which the current ran in the opposite direction that caused the problem. By arranging that the wires on each subsection of the coil assembly all had currents running in the same direction, he greatly attenuated the noise (62). However, all this came at the expense of gradient efficiency and, despite the major improvement, he regretted that this was the one major problem with MRI for which he had not found the definitive solution.

Peter was a gifted physicist, but regarded himself as primarily an inventor. He had the ability to see the big picture and the tenacity of purpose to deliver it. Faced with a challenge, his fertile mind would generate multiple solutions—not all of them feasible! His research group acted as the ‘intellectual filter’, though persuading Peter, or PM as he was generally known to his group, that a new idea might not be his best could itself be a major challenge. He drove himself hard, and expected the same of his team members. They understood why, and experience in the Mansfield group was the foundation for many highly successful careers in MRI. Peter was a modest, soft-spoken, shy man who rarely opened up, except to family and close friends. He was always courteous, generous and fiercely loyal to those who worked for or with him.

MRI brought about a revolution in diagnostic radiology in the closing decades of the 20th century, and it is now hard to countenance medical practice without it. Approaching 100 million conventional MRI procedures are conducted annually, and fMRI, underpinned by EPI, has brought about a second revolution in our ability to investigate the functioning of the human mind.

FAMILY AFFAIRS

Peter married Jean Kibble on 1 September 1962 at St Giles Camberwell shortly before leaving with her to spend a one-year postdoctoral fellowship in Urbana Illinois. They had two daughters, Gillian and Sarah, and four grandchildren. He died at the City Hospital, Nottingham, on 8 February 2017, following a major stroke.

Peter’s life was his work. Yet he found time to maintain his proficiency in foreign languages, especially German and Russian, and, following his retirement in 1994, was able to indulge his passion for flying. He first acquired his private pilot’s licence on fixed wing aircraft and later graduated to helicopters, for which he also obtained a private pilot’s licence. This love of flying was reflected in the undergraduate project he offered final year students—the development of a man-powered helicopter. Unlike MRI, it never really got off the ground, but the undergraduates had a lot of fun in the attempt!

AWARDS

1983 Gold Medal of Society of Magnetic Resonance in Medicine
1984 Royal Society’s Wellcome Medal
1987 Fellowship of the Royal Society
1988 Duddell Medal of the Institute of Physics
1990 Royal Society’s Mullard Medal  
1993 Knighthood  
1995 Gold Medal of European Association of Radiology  
2003 Nobel Prize for Physiology or Medicine (shared with Paul Lauterbur)  
2006 Gold Medal of Royal Society of Medicine  
2007 Times Higher Award for Lifetime Achievement  
2008 Portrait by Stephen Shankland commissioned by and on display in the National Portrait Gallery  
2009 Millennium Medal of the Medical Research Council  
2009 Pride of Britain Award  
2011 Honorary Doctor of Science, University of Cambridge  
2013 Freedom of the City of Nottingham

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AUTHOR PROFILE

Peter Morris CBE

Peter Morris CBE studied theoretical physics at Cambridge before undertaking a PhD in solid state NMR in Nottingham supervised by Sir Peter Mansfield. In the late 1970s he was part of a team that constructed a whole-body MRI system, which is now in the London Science Museum. He helped to establish the fundamental principles of MRI (‘Mansfield & Morris’) in 1982 before moving to the Medical Research Council’s National Biomedical NMR Centre and then to Cambridge as a university lecturer in biochemistry. He returned to Nottingham in 1990 as Professor of Physics and, following Sir Peter’s retirement in 1994, became director of the Sir Peter Mansfield Imaging Centre. He retired as director in 2016, but continued to lead research programmes on the development of techniques for ultra-high-field MRI, multimodal imaging (fMRI, EEG and MEG) and the use of $^1$H and $^{13}$C MRS to understand the metabolic basis of neural activation. He was awarded a CBE in the 2016 New Year Honours in recognition of his services to science and medicine.

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