Inside Hugh's Head

Building the first whole body NMR Imager

Peter Walters

19 Aug 2022

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Author Biography

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Empl: Ferranti Ltd Bracknell 1974-77, EMI/Thorn EMI Central Research Laboratories 1977-1996. Scipher 1996-1999. UK National Contact Point ICT 1999-2015.

THIS IS ABOUT NUCLEAR MAGNETIC RESONANCE - A BRIEF EXPLANATION MIGHT HELP:

'the holes in the sky are everso small – that's why rain is thin' - Spike Milligan

Atoms are tinier still. A hydrogen atom; which is one of the smallest, has in its middle a nucleus comprising a single particle called a proton. This proton spins and is positively charged giving rise to magnetic properties. If you put it in a magnetic field, it will try to line its magnetic field up with the external one. When it tries to do this its angular momentum (from the spin) produces a reaction force which causes the proton's spin axis to precess around the external field direction.

https://upload.wikimedia.org/wikipedia/commons/8/82/Gyroscope_precession.gif

In the case of the proton the rate of precession is determined by the magnitude of the external field.

The proton can be in one of two states either aligned with the field or against it. These two states have slightly different energies. A further magnetic field at right angles to the applied field rotating in synchronism with the precession can transfer energy to protons in the lower energy state and promote them to the higher. The promoted protons can decay back to the ground state by radiating the excess energy as magnetic fields at the precession (or Larmor) frequency and return to the ground state.

These frequency dependent energy transfers constitute Nuclear Magnetic Resonance.

The energy difference between the two states in 'reasonable' applied fields are in the region of megahertz, and are therefore small when compared with the energy of thermal noise at 'room' temperatures.

Following work described below, and very much more Nuclear Magnetic Resonance (NMR) outlined above, has been used to create images of structures within the human body. This application has become known as Magnetic Resonance Imaging (MRI) (avoiding the frightening word 'nuclear').

1. Peter Walters – the early years

A Cornishman born 'to' Newquay in 1944, thence to Exeter in 1950, and Hele's Grammar School where I was not into sport, but enjoyed science and scouting. I pursued Photography, making things in meccano my 00 electric Hornby train and built a crystal set; which involved a bow and arrow in successive attempts to place a long wire high up into a nearby pine tree. I secured 'O' level passes in Eng, Fr, Geog, Chem, Biol, Physics, Maths.

Teenage impatience led to my leaving Hele's half way through A levels (Chem, Phys, Bot, Zoo) to work in a shop, where I learned about interacting with people. I started being involved with lighting at the local amateur theatre and began to gain an appreciation of theatrical discipline.

Three years later I worked out that my interest in science was not being used. A simple analysis found that science would be used in a number of local undertakings including the Royal Devon & Exeter Hospital. I looked there for opportunities. I secured a place to study Radiography. It took 3 years to cover the twin specialities (studying human anatomy in some detail and meeting Physics again 'in pictures'). The resulting Society of Radiographers qualification led to a job as Medical Physics Technician at Plymouth General Hospital doing a wide variety of things (radiotherapy planning, isotope handling, calibration of radiotherapy machines, maintenance of electronics. design of safety equipment ..) for the (ex RAF) hospital Physicist: Ron Buchan.

In 1968 Plymouth Technical College had acquired an IBM 1130 computer, which had its own air conditioned room, and servants. They ran an introductory FORTRAN IV course on a Thursday evening for the general public. I decided to go, but failed to persuade Ron to pick up the fee [computers weren't going to be that important in medicine]. So I paid for myself, and have never regretted it.

One evening at the end of his clinic one of the Oncologists John Brindle - had a word with me about my future, suggesting that I should do a degree. In initial steps in that direction I was intimidated reading the London University Physics syllabus - printed on 'prayer book paper' in 7 point Times.

By chance a few weeks later I took a telephone call from a gent who wanted his nephew to come to work at 'my hospital' on a six month sandwich from his Physics degree course at Portsmouth. I told him that it wasn't actually 'my' hospital, pointed him to Ron and exchanged some information about the course.

The Portsmouth syllabus was offset printed on art paper, in 11 point Helvetica with a scholar's margin - much less terrifying.

A month or so later I was on a train to Portsmouth, clutching a bag of sandwiches which my mum had made, to see Dr Ken Martin the deputy Head of the Physics Department at Portsmouth Polytechnic for an interview. After a few minutes of interview having confessed that the last maths exam I had done was 'O' level, 12 years earlier - he said "Don't worry we'll sort all that out when you come up in September, but you'll have to work hard ! ". I was in! - I had a place on their CNAA Honours Degree course in Applied Physics.

Taking Ken at his word I made a start on the maths. I went to stay with a friend in Teignmouth for a few days that summer, I recall sitting in a deckchair on the Den, a grassy area near the sea working my way through Intermediate Algebra Made Simple - The chapter on Determinants came in really handy later on in the Vectors course.

My 'thin' sandwich course took 4 happy years - with the first 3 summers being spent on sandwich at various technical establishments: Road Research Lab, ICI Fibres in Wales, and AERE Harwell. My attendance at 'the poly' was facilitated by a Mature Student grant from Plymouth City Council. Which paid for accommodation, [boarding with 11 others at Mrs Johnson's in Southsea]. Also some books, the odd pint of beer and beans & chips at a staff / student cafeteria in an old stable building across the street from the Physics building in Park Road.

In my first week I met Henry Rattle my first year tutor, he helped me over the jolt from 'civvy' street into student life. Henry worked in the Biophysics group, where they were interested in the structure of Histones. His contribution being Nuclear Magnetic Resonance spectroscopy. On his desk there was a little model of the Eiffel Tower and a gyroscope, with which he would demonstrate gyroscopic precession. We also looked at the source of the signal being derived from the difference in population of the two different energy states with for example a million protons in one and 1,000,001 the other. This determines the small signal to noise ratio found in NMR studies. So within a few weeks I had a vague idea of what NMR was about.

At the end of my third college period I was bound for Harwell, where I learned a lot. I worked for Dr John Rivière on early work on the calibration of Auger Electron Spectroscopy. John (for whom French is his mother tongue) impressed upon us that 'the data are' is good English. Accommodation was at Rush Common House an AERE hostel in Abingdon. Here there were many similar souls, a great deal of fun was had including learning to punt from the 'right end' on the Cherwell. Less adventurous evenings involved Cribbage at the Spread Eagle, or occasional visits to pubs further away: the Barley Mow, the Perch, etc. Some of the chums worked at the Atlas Lab, and some at The Rutherford Lab (RHEL) - adjacent to Harwell, but on the other side of 'the wire'.

Around this time I found that if I was trying to solve a particular problem, sometimes when I awoke in the morning the solution, or its makings would have appeared in my head overnight.

All good things come to an end, and by September I found myself back at 'The Poly' for my final year - living in Rees Hall with a room of my own. By this time the Applied Physics student group was pretty well integrated. We had some compulsory courses, on Properties of materials, Computing (in FORTRAN again), etc, others were elective - my electives were Molecular Spectroscopy, Microwaves, and Nuclear Instrumentation. I spent a day a week on my project on dispersion in alumina microstrip, which I first had to make. There was also the 'milk round' where large companies came to Portsmouth and selected those they might want to interview further. I recall interviews with EMI Electronics, Ferranti, and IBM.

My mum sadly passed away at around this time.

We had a course in Quantum Mechanics given by Dick Jenkins, which none of us really understood, but then Quantum Mechanics is a topic which even Feynman confessed that he didn't fully understand. It included the maths describing the behaviour of a particle in a box, referring to Fourier Transforms (FT) as a solution to the equations. FT pops up all over the place, for example providing means to analyse the sound of a piece of music as individual frequencies of the piano notes played, without observing the player.

Coming up to finals - I looked at the syllabus for my courses, and found that NMR appeared in four of my courses. So I really paid some attention the maths which describes the NMR phenomenon: The Bloch Equations. I understood them and could write out the maths 'blindfold'. I did not concentrate similar effort at being able to answer an arbitrary Quantum Mechanics question. My gamble paid off as NMR appeared in two papers.

During supper on the Thursday evening before finals I got a telephone call from IBM wanting to know there and then if I was going to accept their job offer. They admitted that they were unaware that I was to start finals in 4 days time. I didn't accept T.J. Watson's large shilling.

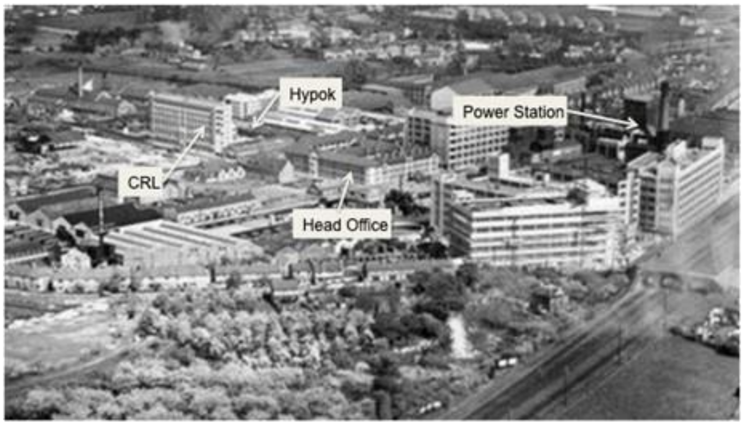
The exams started on the Monday - I recall Christine Johnstone, a colleague who drove a lovely old Morris traveller, arriving by car with a bicycle tied to the roof - by way of a lifeboat lest the Morris break down on the way.

After a heavy week of exams it was nearly all over. I went away with old friends for a week sailing on the Norfolk Broads. Then it was viva time: Professor Conn the head of Physics at Exeter University came to give us our individual 15 minute grilling. I went in and we chatted for a few minutes about my project and things. Then he said 'Tell me about atoms', 'What do you want Waves or Particles?' I replied. The Professor's response was 'Go Away!' I was out in barely 10 minutes. I had got a First Class degree!

2. Going to work

I first went to Bracknell to work in Ferranti's Digital Systems division where they made military computer systems. I was given the Systems Research Lab to run. We had a 24 bit FM1600B computer (used on Type 21 Frigates, etc) It was based around paper tape (magnetic drives were not robust enough to go to sea on warships in the Atlantic winter) and had multiple displays. Terminals that we had in later years were not yet in use at DSD, we used KSR33 Teletypes. I learned to program the 'B' in machine code using the switches, about the operating system and interrupts, to write the odd bit of assembler and the use of the fiendish linker. We would do demonstrations to visiting senior naval visitors after they had been to lunch. We would set these up to be relevant to the visitors, having been told by the host at coffee time what they were interested in. It was fun to see the expressions on their faces when they saw our computer sketches of what they'd only been imagining a couple of hours earlier. The theatrical discipline came in handy.

After a while having fun at Bracknell I realized that the effort I had spent on the mathematics was not being used at Ferranti. I started to look around, and spotted a small fairly general advert in the Thursday's Telegraph for research engineers at EMI, I went to an interview at their site at Hayes, Middx.



Aerial View of EMI site at Hayes Middx

I met Neil Robotham, a friendly personnel officer with a sense of humour at their head office in Hayes. I was to visit three offices at their adjacent Central Research Laboratories (CRL)

EMI's Central Research Laboratories

The first interview was with Doug Wotton who ran the Microwaves department, where I blew it by failing to adequately describe dispersion. The next was with Steve Bates who ran the x-ray scanning group, I think that my Radiography and computing went down reasonably well. Finally I was shepherded out into a long wooden shed at the rear into the office of Hugh Clow.

Recent picture of Hugh Clow

Hugh sat me down in a chair beside his filing cabinet and said 'we are working on medical scanning using Nuclear Magnetic Resonance' [this, it seems was usually the cue for the candidate to collapse in a heap]. My immediate riposte was 'Oh the Bloch Equations'. So I had a new job.

I found a garret in Ealing and started the daily rail commute to EMI's Central Research Laboratory (CRL) in Hayes.

EMI's Research Director was Bill Ingham who ran the labs, with the help of a number of Assistant Directors including: Sid Webley (who looked after Materials and Devices) and Alan Blay (Systems). There were about 350 staff at the time.

There was one figure at CRL, who I will mention immediately. Godfrey Hounsfield, the inventor of the x-ray Scanner. At this time he was absorbed in work to improve the CT scanner – reducing the scan time and increasing the spatial resolution. The story of Godfrey, or Godders or H as he was known is told elsewhere. http://gnhounsfield.org. He was interested in NMR and became a friend.

As far as the NMR project was concerned - Godfrey, Steve Bates, and their people had mastered the business of speedy image reconstruction from absorption data from projections of a slice of a body using Filtered Back Projection. This was to be very useful in our NMR project.

3. The magnetics department

The Magnetics Department was part of Sid Webley's domain. It was led by Ralph Pearce. There were a number of us working on various topics, such as magnetic tape formulation and secure credit card stripes. The NMR work was led by Hugh Clow, who had started on the topic in August 1975. The NMR project officially commenced on 25 Feb. 1976. with the issue of its charge number (73002/28001). Hugh was joined by, Eric and Dr Percival. I joined the team in the early summer.

The most remarkable colleague was Dr W. S. Percival we used to refer to him as 'Perce' (but never to his face). He was a charming, precise and remarkable engineer. He had worked for CRL since the 1930s and had retired at 65. He had then started his 'second career' returning to CRL on the Ealing train two days a week to do theoretical analyses of problems and projects. He was one of the fathers of Electronics, having started out in the early days of wireless as a journalist for Scott-Taggart's Radio Press. He joined EMI to work on the development of valve electronics, and finished with well over 100 patents I got to know him quite well through conversations on the train: we both lived in Ealing.

I learned that he had, for reasons of political belief been excluded from 'war work' and his moral views were still strong: On his non working days he would have the newspapers in the mornings The Times (which still had personal advertisements on its front page) and The Daily Worker "for a balanced view".

Dr Percival had been involved in early electronic television, and amplifiers, both for high power radio transmitters and for recording purposes at the Abbey Road studios. I recall him saying "when I worked on Abbey Road" - I thought immediately about the Beatles LP [Had Perce actually worked with The Beatles ?] - No! - he meant the valve electronics of the recording studio!

Dr W. S. Percival

Dr Percival made a major input to the NMR project by developing a model of the signal to noise (SNR) ratio from first principles. SNR is always of major importance in NMR.

The other member of the team was 'Eric' (a pseudonym at his request), a remarkable practical engineer, who aside from doing an Open University degree in his spare time, was into gliding, and became an airworthiness inspector. He really understood the strength of materials. Eric had been Hugh's right hand man for their previous project on vacuum coating of metal recording tapes. He was a quiet northerner, who rarely came to lunch with us preferring to bring his own sandwiches. He shared a house with Hugh in the Maidenhead area.

3.1. Dr Hugh Clow

Hugh was our immediate boss, and is a good friend. He lives in the north of England and enjoys walking in the hills. When I was writing this I asked him if he had any thoughts to share.

"In the Spring of 1975 I was working on evaporated magnetic tape. Daphne, my wife was in the last phases of breast cancer. In May or June I went to see Bill Ingham our Research Director and he agreed that I could have time off work until she died.

She died on July 22nd.

I went back to work in August and was surprised to be taken off magnetic tape and given a new job to work with Percival to look into the feasibility of making a medical scanner using NMR, not X-rays.

I don't know who introduced EMI to this concept. I certainly wasn't contacted by Mansfield. I think that Godfrey Hounsfield must have been involved, possibly tipped off by someone from Nottingham. Within a few days I found myself driving Sid Webley to Nottingham to see Prof. Raymond Andrew.

Sid Webley had recruited me from the physics department at Nottingham in 1959. This was before the start of NMR work there. I worked for Prof. Bates, and worked on magnetisation reversal processes. Lesley Fleetwood Bates had worked for Rutherford at Cambridge before becoming the physics prof. at Nottingham. When Prof Andrew was taking us to lunch a voice piped up saying "Is that you Clow you old bugger, still wasting your time in industry?" That was Prof. Bates.

I knew nothing about NMR, I think that Percival thought that it would just involve a few calculations to prove that it wasn't feasible, whereas over the next year it was just looking to be feasible but very very difficult.

The signal to noise ratio.

In the first few days Percival calculated that the signal would be very small, and so the signal to noise ratio was going to be critical to the feasibility of the concept. This depended upon the resistance of the detection circuit. Even if the resistance of the circuitry was low the resistance of the person being scanned would add to the noise. Very little was known about the resistance of a human body at 6 MHz, and so we measured the "Q" value of a suitable coil with one of us inside it. This gave Percival a number to use in his calculations. I think that when we came to doing real scans we found that the situation was not quite as bad as we had estimated."

I explained this to myself as follows: The model which Hugh and Perce had taken was that the body could be assumed to be a large container filled with salty water, in which circulating electric currents could have large diameters.

However in the human body there are organs which are in general surrounded by connective tissues, I had observed such in operating theatres which I had visited in the Radiography training. These I surmised were of lower conductivity, (imagining them to be polythene bags) hence breaking up the large volume of the simple model into a number of smaller but separate circulation cells.

4. An experimental machine

When I arrived at CRL the spatially resolved NMR idea had been revealed by Paul Lauterbur of Stony Brook Ny., to Prof Raymond Andrew and others at Nottingham (Hugh's Alma Mater). The initial connection between that and CRL is not clear to me. Hugh and Dr Percival had carried out a study, which suggested that a medical imager based upon NMR might (just) be possible.

The next step was to produce an outline design concept.

We set out, with the blessing of our Research Director and the EMI board to make a study of the creation of an experimental NMR machine big enough to hold a person, with a view to building one and taking pictures with it.

We didn't know precisely how to do it, but we had some basic knowledge, a deal of enthusiasm and a determination to find out. In retrospect there were big holes in our knowledge. We were soon to discover challenges and solutions which we had not anticipated, but that's what they call research.

Best of all was that our group was funded at least for a few months.

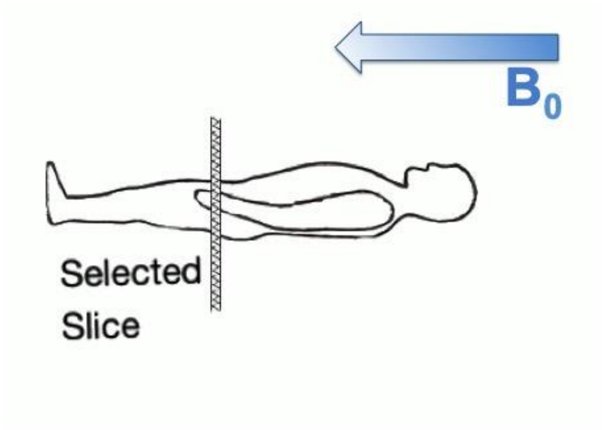
The founding idea for MRI arises from the NMR Larmor Equation for the proton in a Hydrogen nucleus (typically in a water molecule).

Larmor Equation: $\omega = \gamma \times \mathbf{B}_0$

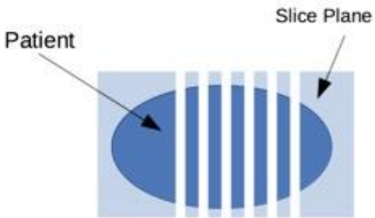
This defines the Nuclear magnetic resonance frequency = $\omega/2\pi$,
where $\mathbf{B}_0$ is the magnetic field in Tesla,
and γ the gyromagnetic ratio,
which for the proton is known to high accuracy
(in units of $\gamma/2\pi$ = 42.57747892(29) MHz / Tesla)

This says that the resonance frequency is dependent upon the local magnetic field strength. Which means that in a given distribution of resonant protons the RF signal from those in a particular place may be found from the signal magnitude at the frequency determined by the field magnitude in their locale.

The idea then is to place the subject on the axis of a steady uniform magnetic field, to which is added a pulsed gradient field from head to toe (both fields are in direction B_0 in the diagram below). A pulse of RF field at a specific frequency then promotes resonance in protons in a particular slice of the body. The slice lying in a plane normal to the static field and the added gradient. The gradient is then removed.



Thereafter a transverse gradient is added, which causes the protons in different stripes normal to the gradient to precess at different frequencies. The magnitude of the signal at a given frequency representing the sum of those from all the resonant protons in a stripe across the slice.



Diagrammatic representation of 'stripes'

These stripe signals at discrete frequencies are essentially analogous to the signal derivation process used in the x-ray scanner. In that case the individual elements represent the net x-ray absorption in the stripe. These sums are referred to as 'edge values'. In our case they were the sum of the radiofrequency signal at the particular frequency of the protons in the stripe.

On this basis CRL management saw an opportunity to build an NMR 'front end' for an existing x-ray scanner. This was the just the start of the idea, although time saw that idea develop in major ways.

A simple view of the machine operation would then be as follows. Initially the subject is lying along the axis (z direction) of a strong static magnetic field. The spins in the subject at thermal equilibrium.

1. Add a magnetic field gradient in the z direction
2. Apply RF pulse rotating in the xy plane at the Larmor frequency of the slice
3. Remove z gradient
4. Apply transverse gradient in the xy direction at a particular angle

5. Collect the minute, time varying RF signal
6. Remove xy gradient
7. Wait for spin population to return to equilibrium
8. Repeat from 2 using varying transverse gradient directions

The spin density in the various stripes would appear as a signal magnitude at a particular frequency.

When I arrived Hugh and Dr Percival were thinking that they could extract and analyse the NMR signal to provide 128 'edge values' for a particular transverse direction. This could then be fed fairly directly into an x-ray scanner display console. The means of extracting the individual 'stripe' signals would employ 128 phase sensitive detectors each tuned to the frequency of an individual stripe.

This seemed like a big box of electronics, and I worried about it in my Ealing garret. The combined time varying signal was something to do with the combination of resonance signals at different frequencies. Somewhere in the back of my brain was the recollection of a Quantum Mechanics lecture some 5 years earlier which talked about Fourier Transforms, maybe it was something to do with 'a particle in a box'.

EMI had quite a good library in nearby Head Office. I walked over and met Monica the Librarian who pointed me in the right direction. I did a bit of reading and convinced myself that if we gathered the NMR signals from all of the resonant stripes together as a waveform in time, and then subjected this to a Fourier Transform, the result in the frequency domain (which we had fixed in a spatial sense by the transverse gradient) would be equivalent to all of the individual edge values placed side by side in frequency space.

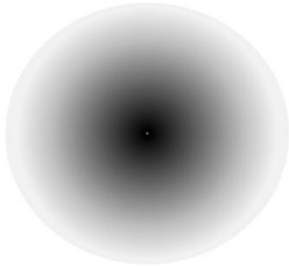
I shared an office with Hugh and Eric. Dr Percival used to come in to the lab on Tuesdays and Thursdays, he would come our office early in the day, where the regular progress discussion occurred. He would return later with typed up notes of his days thinking just before going home time.

So one 'Perce' morning I launched my Fourier Transform notion. Dr Percival did not immediately take to it. It took several weeks of discussion amongst the three of us before it was accepted. A paper by Ernst seemed to support the FT idea. The idea gradually became clearer as we understood more about Fourier methods, and read parts of Bracewell's book.

The EMI x-ray scanner reconstruction process in use at the time was called Filtered Back Projection. Sets of edge values were obtained by measuring the x-ray absorption for a number of parallel stripes. Numerous data sets were obtained at different projection angles (540 views in 180° for the CT5000 x-ray scanner). These data were then projected onto a display array to reconstruct the image.

If, for example the object was a single high density (black) blob in the centre, the edge values from all directions would be similar, having a high central value with low values on either side. If such edge values were simply projected into the array then the high value in any direction would create a dark diametric stripe right across the image. Adding similar edge value sets from multiple directions would sum to give a dark central blob.

A number of edge values summed into an image array



Indication of result of projection of large number of plain edge values

But there would also be a surrounding halo artifact all over the whole image. This is indicated in the diagrams above.

It was necessary to overcome this if fast x-ray scanning was going to happen in 1970s. This was also true for MRI.

One of the engineers working with Steve Bates' x-ray scanner department, Chris LeMay, (who had a degree in Geology) came up with a solution 'The Circle Method' [US Patent 4,114,042] - pre-processing the edge values using a filter function removed the artefact. This was a convolution in the linear-space domain which is equivalent to a point by point multiplication in the Fourier domain.

We were going to use the Fourier Transform to convert between the time and space domains. The TIME domain is where we sampled and recorded the time evolving NMR signal. Its transform to the FREQUENCY domain then shows the intensities of the frequency signals which combine to create our time domain signal, and actually represent spin densities in the equivalent SPACE domain. Because we had coded space in terms of frequency by the NMR process and linear field gradients.

This is quite complicated and takes a while to get used to - but in time one gets to imagine functions and their transforms. For example a continuous sine wave in time transforms to function in frequency space which has a high value at the frequency of the sine wave and is zero elsewhere

5. The main field (B_0)

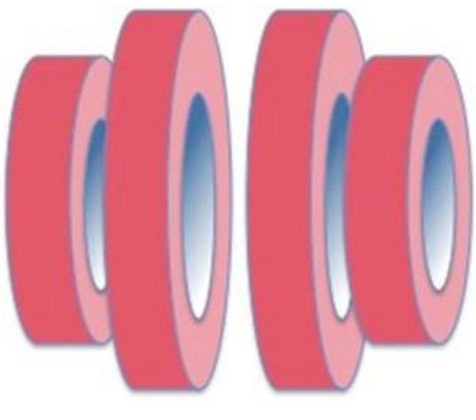
Dr Percival had worked out from first principles, (in CGS units), an expression for signal to noise ratio, which showed that this improved by a power law with increase in B_0. We had to get a powerful magnet big enough to contain a person and we had a limited budget. It is now easy to buy a body sized magnet - indeed there are many thousands worldwide, but ours was going to be one of, if not the first. A superconducting magnet was a possibility, but would likely be very expensive and have ongoing needs for cryogenic support, whereas a 'normal' electromagnet simply required power and probably cooling water.

Hugh had visited Stony Brook on Long Island and had a multi topic meeting with Paul Lauterbur, at which he learned that Paul was ordering a normal electromagnet from nearby Walker Magnetics. Hugh asked Walker for a quote for a 0.1 Tesla magnet with a specified uniformity. With a base field of 0.1 Tesla the proton resonance frequency was going to 4.26 MHz.

We made a similar request to the UK company Oxford Scientific, whose response took a long time coming. Both offerings comprised 4 coils arranged as twin Helmoltz pairs the outer pair being of smaller diameter. This agreed with an observation by Prof Raymond Andrew of U Nottingham, who I recall said that for maximum uniformity the current paths should lie on the surface of a sphere. The Oxford design used copper conductors of smaller overall cross section.

Walker opted for broad windings of aluminium tape glued to an aluminium plate which incorporated cooling water channels.

The question was then 'would the Walker design deliver the required field? I recalled from my Harwell days that the people at the neighbouring Rutherford Lab (RHEL) spent a deal of effort designing magnets for beam steering in their particle accelerators. Speaking to one of the Abingdon chums I quickly found that the leading light in magnet design was Dr C W Trowbridge, so we arranged to go and see him.



Walker Magnet shape

Hugh drove us up to RHEL and we chatted with Dr Trowbridge, who took some details and sent one of his men to talk to their IBM360. About 20 mins later he returned with a small stack of green and white printout and some plots of the predicted field. It was all done in less than an hour, we thanked Dr Trowbridge, and went back to the car park. Hugh then said 'guess we better go for some lunch'.

Don't worry I said - I know just the place and it's on our way back. So off we went and I navigated Hugh down some country lanes heading for The Barley Mow at Clifton Hamden. After about 20 mins I could tell that Hugh was beginning to wonder if this was a wild goose chase. Then as we came round the bend I announced the pub, to find that it was represented by some blackened smoking stumps - it had burned down a couple of days earlier.

The restored Barley Mow (now a Chef & Brewer)

Not a particularly good way to impress one's new boss. We went to The Plough just up the road.

The Walker design was preferred.

6. Electronics

As the design grew it was obvious that we would need help with the electrical engineering associated with receiving very weak signals in the presence of noise and controlling huge currents in the gradient coils. Clearly a problem for Alan Blay's men. We started out chatting to Dr Bull, who seemed a little reticent to join in - he was about to retire. His replacement, Ian Young was much more approachable and enthusiastic. Over the coming months he became deeply involved in the project, growing a team to support it. These included Colin Harrison and Mike Burl. Later and in the construction phase the engineering team included Tom Passmore, Dave Gilderdale, Barry Maufe David Bailes, Alan Collins, and Alasdair Hall who replaced Colin when he left to go to IBM in New England. They became our colleagues, and we worked well together despite the different management units to which we reported.

Although in the early days there were only a few of us working actively on 'the project' money was always a concern. This led us to be very careful with our expenditure.

In pursuit of additional funding senior management approached Department of Health, as they had done previously for the x-ray Scanner. They found some interest and it was suggested that we go along to The Hammersmith Hospital to meet a pair of eminent Radiologists: Professors Frank Doyle, and Robert Steiner; to try our ideas out on them. It was fixed up for Ian Young and I to visit them for lunch and a chat. They received us well and were most polite about our strange ideas. [I recall meeting Prof Steiner at a reception at The Barbican some years later, and reminded him of our first meeting, he shared an opinion that they had thought that maybe we were a little crazy]

6.1. The z gradient

The path to a design was not always straightforward. For example we were going to need to provide a pulsed magnetic field gradient along the axis of the magnet known as the z gradient. This was to be produced by a current flowing in a reverse connected pair of Helmholtz coils. These coils were to be made from 25mm wide by ~ 2mm thick copper tape using 8 or 10 turns with a diameter of about 75cm. Clearly some sort of amplifier would be needed to drive current in these coils.

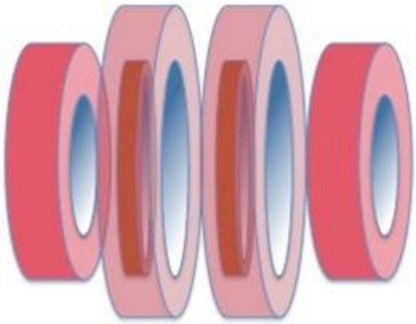


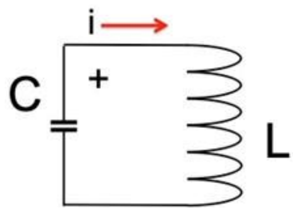
Diagram to show location of Z gradient coils

One Friday early on in the design process Ian came to see us wearing a face as long as November: "You can't afford it" he gloomed. Apparently the cost of amplifiers to drive such a load was huge. So we went home for the week end in a rather depressed state as this news appeared fatal.

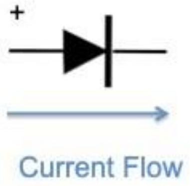
Sitting sadly in my garret I didn't want to give up on this potentially important medical imager. It was all about inductance. We had met this together with capacitance in the course at Portsmouth, for example in solving differential equations about the flow of current in a circuit combining both.

Then I had this idea:

If one were to start with a capacitor charged up to a respectable voltage, and then connected an inductance across the capacitor, what would happen was that as you made the connection you would see a spark, and a pulse of current would flow until the capacitor was discharged. That was not the end of the matter, as the current flowed around the loop the charge would be transferred to the capacitor - but in the reverse polarity from that at the start. This oscillation would continue with a small diminution at each cycle due to any resistance in the circuit.



A bit about Electronics:
There is this device called a diode or rectifier – it will conduct electricity in one direction, but not in the other. It is represented in circuit diagrams by a symbol

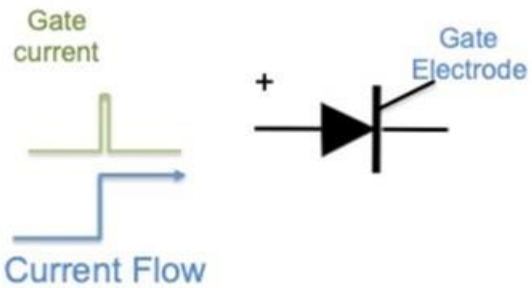


The symbol shows current flow in the direction of the 'arrow'.
[Beware of confusion with the flow of electrons which being negative, flow in the opposite direction]

BUT what would happen if the circuit included a diode? The initial result would be the same, After the initial current pulse we would wind up with the capacitor charged up in the reverse direction. The diode would then be reverse biased and no further current would flow.

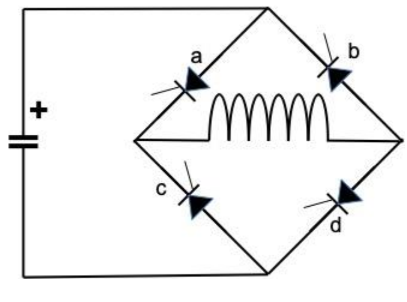
We would have generated a single magnetic field pulse. The next similar pulse would require the capacitor to be used in the opposite direction to produce the gradient field in the same direction, and would need to have a bit more charge added to it to make up for any resistive loss.

A bit more Electronics: The `Silicon Controlled Rectifier'
This device is the second cousin of the solid state rectifying diode just described.



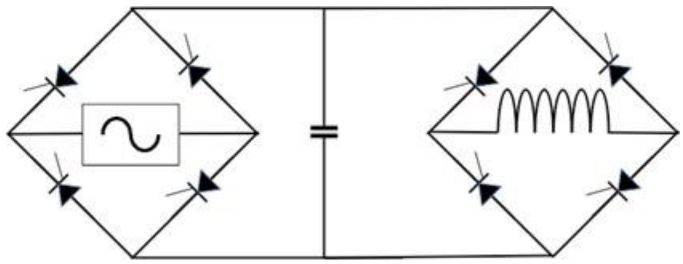
The notable difference is that in its construction an extra element or 'gate' is embedded in the chip. If a current pulse is applied to the gate forward conduction is initiated. This conduction is terminated when the voltage across the device approaches zero.

This switching could be done electronically using Silicon Controlled Rectifiers. A circuit as shown would allow successive field pulses it be given in the necessary sense:



The capacitor is charged with the +ve plate at the top in the sketch. Both SCRs a and d are turned on and a current flow from Left to Right in the inductor occurs. At the end of the pulse the SCRs turn off and the voltage on the capacitor is reversed. In order to generate the next pulse the gates of SCRs c and b are pulsed resulting in the current flowing in the inductor again from left to right in the diagram.

The loss of voltage on the capacitor has to be made up to ensure that successive current pulses are of equal power. This topping up may be achieved by means of a second SCR bridge connected across the capacitor fed from an AC (mains) supply.



The idea was accepted and Ian and his team took it over and decided that they could made physical electronic sense of my wild idea.

There was than a delay whilst we waited for CRL funding for a bigger project including the magnet. During this time I ran some analysis on a time sharing machine looking at shapes for RF pulses by looking for solutions to the Bloch Equations under field gradients.

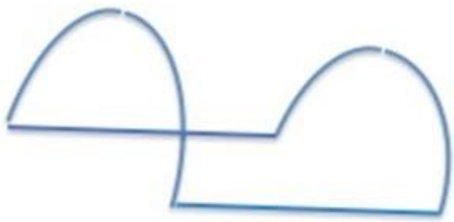
Eric eventually wound the z coils, doing a deal of hard work with frequent use of a wooden mallet and a blowtorch to anneal the tape to maintain the flexibility necessary for the winding process.

6.2. The transverse gradient

From the start these had been envisaged as generated by a set of four rectangular coils for both the x and y directions mounted on the outside of the main magnet. These were wound in copper tape on fibreglass formers. These can be seen in the picture of the magnet on page 19.

In the out turn this design did not work very well, and so a different option was taken for the gradient coils. The originals were retained and used by Hugh and Colin for shimming the static field.

A plastic tube was to be fitted to the bore of the Walker magnet, which carried a number of ‘Saddle shaped’ gradient coils [also known as Golay Coils]



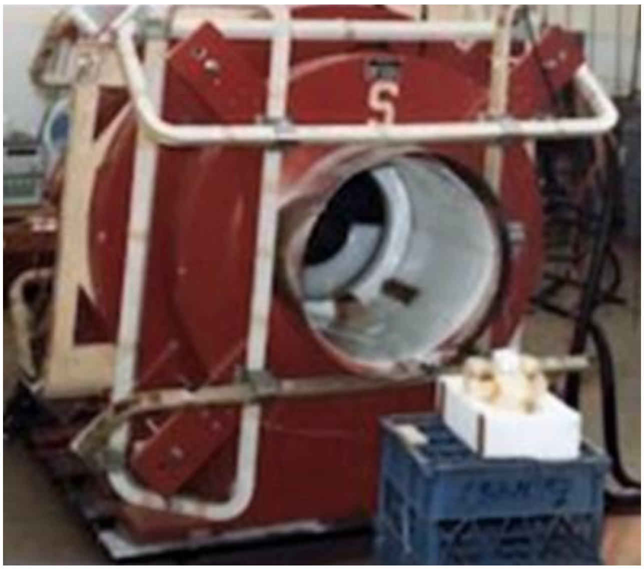
7. Major components

We had a paper design well worked out - a report was made to the EMI Board by the Director proposing the continuation of the project - which involved commitment of moneys to buy the hardware. This permission was not immediately forthcoming. I recall a visit by Board members and making a presentation to them stressing the meaning of the Larmor equation.

Time went by during and we relaxed a little. I worked on a slice selection model solving the Bloch equations in FORTRAN. While living in Ealing I had become a member of The Questors Theatre, and worked on stage lighting there in my spare time. I had been persuaded to undertake the Stage Management of a production of Noël Coward's Hay Fever in May 1977.

Then the magnet money came through. We were about to get very busy at work so I shared my problems with Tim the SM coordinator at The Questors and he arranged a replacement - Lesley Montgomery - who took on the job. I helped in my spare moments, the production was well received. One thing led to another and Lesley later become my wife.

In due course our pretty red magnet came in by air, was delivered to site, unpacked and manoeuvred into place by the EMI site 'heavy gang' and their posh yellow crane. The magnet was set up in 'Hypok Hall' in the wooden CRL annex, where work on high power Klystrons had been done in the past.



The Walker magnet in Hypok with some accessories attached

7.1. The computer system

We were going to need a computer. A few hundred metres down the road from CRL past 'head office' was an EMI Medical building, where they assembled x-ray Scanners, mostly from components bought directly from their manufacturers. Having talked with Steve Bates' folks I learned that EMI Medical used Data General Eclipse machines in the current range of scanners, and were buying them in some numbers at a hefty discount. Other discussions forced us into using assembler to code our reconstruction to keep the time between scan and seeing the image as short as possible. In that way the patient throughput might be kept high.

Steve Bates arranged for me to spend a few days with, one of his programmers, Pete Reid who introduced me to the Data General (DG) assembler and RDOS the operating system. Pete encouraged me to write 'Hello World' and a few more taxing bits of code.

I was given a contact in EMI Medical who I went to see. It seemed that we simply needed an internal purchase order. So we were going to have an Eclipse (16 bit, 32K store), within a very few days, and a Versatec printer - which they also bought in quantity.

We started to outline the software system which was going to be needed and recruited Neil Rutherford to work on software. Neil had previously worked on computer systems for BOAC and was a devotee of CAMRA. He used to cycle to work along the canal towpath. He was also an aficionado of local newspapers, and regularly carried out arguments between two alter egos in the editors letters columns. We both went on Data General programming courses to get our DG assembler skills up to speed.

By now we had a number of consultants from Nottingham University, in addition to Prof Andrew and Peter Mansfield, others included Bill Moore and Neil Holland. I got on very well with Bill Moore, who had done work on Electron spin resonance in garnet crystals, some of which he shared with us. These were used in accurate field measurements necessary for shimming the Walker field.

As luck would have it Bill also used DG computers in his lab at Nottingham. He helped us with our need for an FFT routine, he shared some code with us, which Neil Rutherford set up on the Eclipse.

I recall an interesting wheeze which Bill steered us towards. We wanted to be able to do the Fourier Transform quickly, using code called Fast FT - (FFT) which was described fairly widely in literature. We needed to code this in assembler to run on the 16 bit Eclipse. The input data was going to be 10 bits wide - so the arithmetic only needed to be single length.

An FT operates on complex data - each 'point' being represented by both a real part and an imaginary one $\mathbf{x} = a + jb$. Where a represents the magnitude, and b its phase with respect to a given zero.

Part of the FFT involves a 'butterfly' multiplying the complex pair of values by the sine and cosine of an angle (ωt) representing the time increments along the temporal data. As the sampling rate was to be constant during a scan we could store the sin(ωt) values in a table and look them up directly each time we needed them, rather than wait whilst the Eclipse ran a routine to calculate the values from first principles every time. There was also a way of shortening the table because for two complementary angles sin(a)=cos(90-a) we simply needed to use the compliment of the table pointer to find the cosine of a given ωt from the sine table.

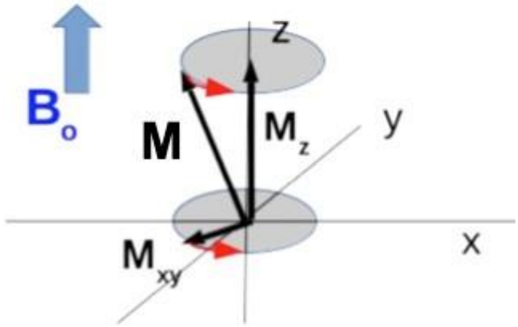
Bill was a good friend, and left Nottingham to take up posts at Harvard. Very sadly he died in 1984 of a heart attack following over-exertion on the racket ball court.

8. Thinking about spins

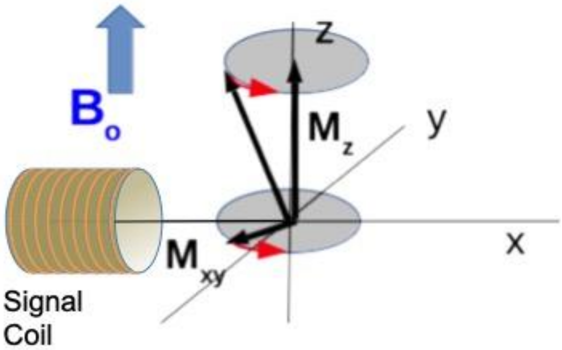
As our involvement with NMR grew we developed ways of thinking from the point of view of the NMR magnetisation vector, and how it was manipulated and interrogated in the imaging process.

To myself I labelled this manipulation spin jockeying. Perhaps it starts out with my old favourite - The Bloch Equations.
[for details see https://journals.aps.org/pr/pdf/10.1103/PhysRev.70.460]

These differential equations describe the precession phenomenon of the bulk magnetisation in the static field, and the results of its stimulation by an RF field at the Larmor Frequency [$\omega=\gamma\times\mathbf{B}_0$]. The initial form, in Bloch's 1943 paper, used Cartesian coordinates, and transformation to polar coordinates was part of the paper.

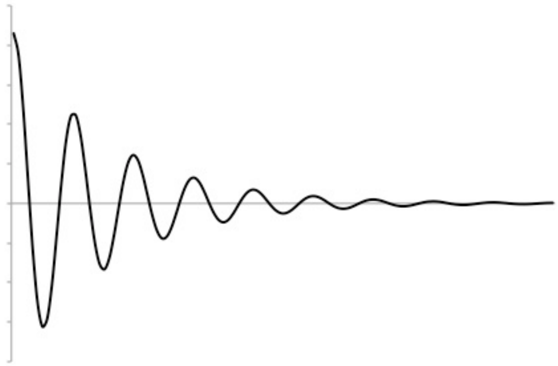


They set out to describe the precessing magnetisation **M** - the resultant of many spins as they become gathered in phase by the RF. **M** may be resolved into two components, one '**M**z' aligned with the DC field $\mathbf{B}_0$ and the other a vector '**M**xy' which rotates about $\mathbf{B}_0$ in the xy plane, at the Larmor frequency.



An RF signal of the resonance is obtained across a coil with its axis in the xy plane which observes the rotation of **M**xy

Initially a brief pulse of RF excitation is applied in the xy plane. This promotes some magnetisation into the xy plane where they may be detected by the adjacent signal coil. The varying signal detected is known as a free induction decay (FID)



Free Induction Decay

The magnitude of the initial signal depends upon the magnitude of Mxy which is determined by the RF field strength and the duration and shape of the RF pulse.

The decay of the signal is of interest, happening by two processes, one (T_1) in which energy is transferred from the resonant nuclei to their surroundings, and the second (T_2) where the individual components of **M**xy loose phase coherence due to local field differences. T_1 is longer than T_2.

The simplest ideas for MRI signal generation and recovery would use the following steps. With the patient in the DC field (in z direction) - and the spins in thermal equilibrium:

1. Add a magnetic field gradient in the z direction
2. Apply RF pulse rotating in the xy plane at the Larmor frequency of the slice
3. Remove z gradient
4. Apply transverse gradient in the xy direction at a particular angle
5. Collect signal
6. Remove xy gradient
7. Wait for spin population to return to equilibrium
8. Repeat using varying transverse gradient directions

In this simple technique the wait could be a number of seconds at step 7, which would make for a rather long overall imaging time.

It was hoped that the differences in signal arising from the relaxation processes would reflect different chemical environments in the body and hence give rise to contrast between different tissues.

Broadly this turned out to be the case. Yet that does not mean that untangling this relationship was simple, many people spent time over the years working on this. For example designing excitation pulse sequences which delivered useful contrast between different tissues.

This effect is of great importance, since from it arises the salient advantage which MRI has over x-ray imaging. The relaxation time which can affect the 'imaged property' in MRI images is itself affected by the chemical environment in which the resonant nuclei find themselves. This is completely different from x-ray imaging which images electron density. Thus x-ray images are about density, whilst in MRI the images can have something to do with chemistry, which from the start I thought might be subject to change as a result of disease.

Further analysis of the Bloch equations frequently leads to change of coordinates from a Cartesian set xyz into a polar coordinate set of the 'rotating frame of reference' often represented by zx′y′. Here one transforms ones viewpoint from one standing firmly on the floor of the NMR room to one 'sitting' on the rotating xy magnetisation vector.

From this viewpoint one can imagine that the RF field drives average magnetisation away from the z direction towards the xy plane at a rate defined by the RF field strength. This theory specifies the duration of RF pulses which are used to drive nuclear spin populations to produce maximum Mxy termed $\pi/2$ pulses, [because the net magnetisation is moved through 90° from the z direction into the xy plane.]

One of the applications of multiple RF pulses is that it gives rise to the possibility of more complex signal generation and recovery schemes.

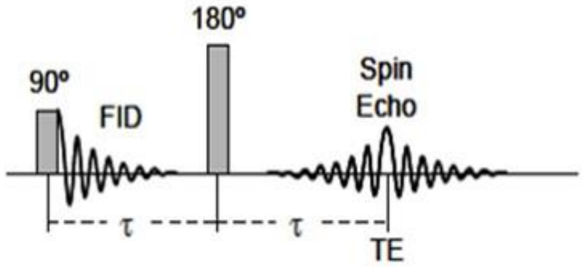
Longer RF pulses can drive **M**xy through the xy plane. These are termed π pulses. These can give rise to 'spin echoes', which were discovered by Hahn in 1950 [Physical Review. 80 (4): 580–594].

I met Erwin Hahn at an NMR conference held at Nottingham University, and over a beer one evening he told me how he had accidentally discovered the spin echo phenomenon. In typical physicist manner his curiosity was stimulated by the unexpected and he went on to publish the detail later in 1950.

It goes like this: An NMR sample is subjected to a 90° ($\pi/2$) RF pulse promoting magnetisation in the xy plane. This generates a resonance signal, which decays as the nuclei 'relax'. This signal is a Free Induction Decay (FID). The decay occurs as phase coherence between the discrete moments is lost by interaction with local field variations.

After this signal has decayed, at a time τ, a 180° (π) pulse is delivered.

A short while later a new signal appears, growing from the noise into a peak at 2τ which then decays in a manner similar to that of the earlier FID.



What is happening here is that the original signal decays by a T_2 process as the individual spins in marginally different environments become dephased. The π pulse inverts these spins across the rotating x'y' plane where they then experience the reverse dephasing to come back into phase generating the 'echo' signal at 2τ.

Spin echoes may be used in signal generation and recovery as a means of hopefully mitigating the longer imaging times needed by simple FID, which simply waits for the starting equilibrium to be re-established. This is done by following the single xy gradient step with a number of spin echo like steps.

In casting around to find ways of improving signal to noise ratio we discovered reference in NMR spectroscopy literature to a pulse sequence for a 'Driven Equilibrium Fourier Transform' method termed DEFT.

In DEFT the initial (spectroscopic) NMR signal is created by a sequence of RF and magnetic field pulses. Once the signal has been collected, a further set of pulses is applied in the reverse order and reverse sense to those which originally moved the spins from their equilibrium state. This returns the spins to a state close to the equilibrium in which they started. All that is then necessary is a shortened wait, thus decreasing the time between successive signal extractions.

We applied modifications to the DEFT idea to allow for the complexity of the MRI sequences. This was patented as GB1548948 (listing Clow, Percival and Walters as inventors). We did not use this sequence in the experimental machine, as the fields which the Walker Magnet generated did not exhibit sufficient stability.

Enough of this complicated stuff - suffice it to say that the introduction of rotating frame leads one to start to imagine 'living' in that frame, and experiencing the effects of the various fields as thought experiments.

I used to go to lunch with Ian Young's 'front end' expert; Mike Burl. Quite often we would go for a stroll along the north bank of the Grand Union Canal to Hayes town and would inevitably fall to talking about the project. We got on very well, having both been 'late starters'. There was a deal of anthropomorphism about - he and his wife had a yellow car which they used to call Buttercup.

We would speak of the need for the machine to learn how to work, and would talk about spin behaviour etc. For example we needed to sample the spins in the slice as they dephased under the transverse gradient across the slice to generate the temporal edge value signal in the time domain. This was to be caused by the application of the xy field gradient. We found that the growth rate of this gradient field was not square edged as our naïve model assumed: it was time variant, taking time to build to the full value. Mike used to describe this as due to the field 'soaking into' the structure of the Walker magnet.

This slow growth of the spatial dephasing of the signal was non-linear hence the first few samples taken early in the gradient pulse would appear to have been taken too soon - resulting in nonuniform sampling in terms of the actual gradient.

A bit of thinking about this led me to come up with the idea of non-linear sampling delays - I called it 'stretched time sampling', which I shared with the rest of the team. The concept was to adjust the early sampling intervals until the integral of field and time reached the desired /notional 'flat topped' value. It gave rise to a patent US4315216A. Notice that this time stretching would not effect the FFT input values as they had by the use of stretched time had their sampling times adjusted to restore linearity.

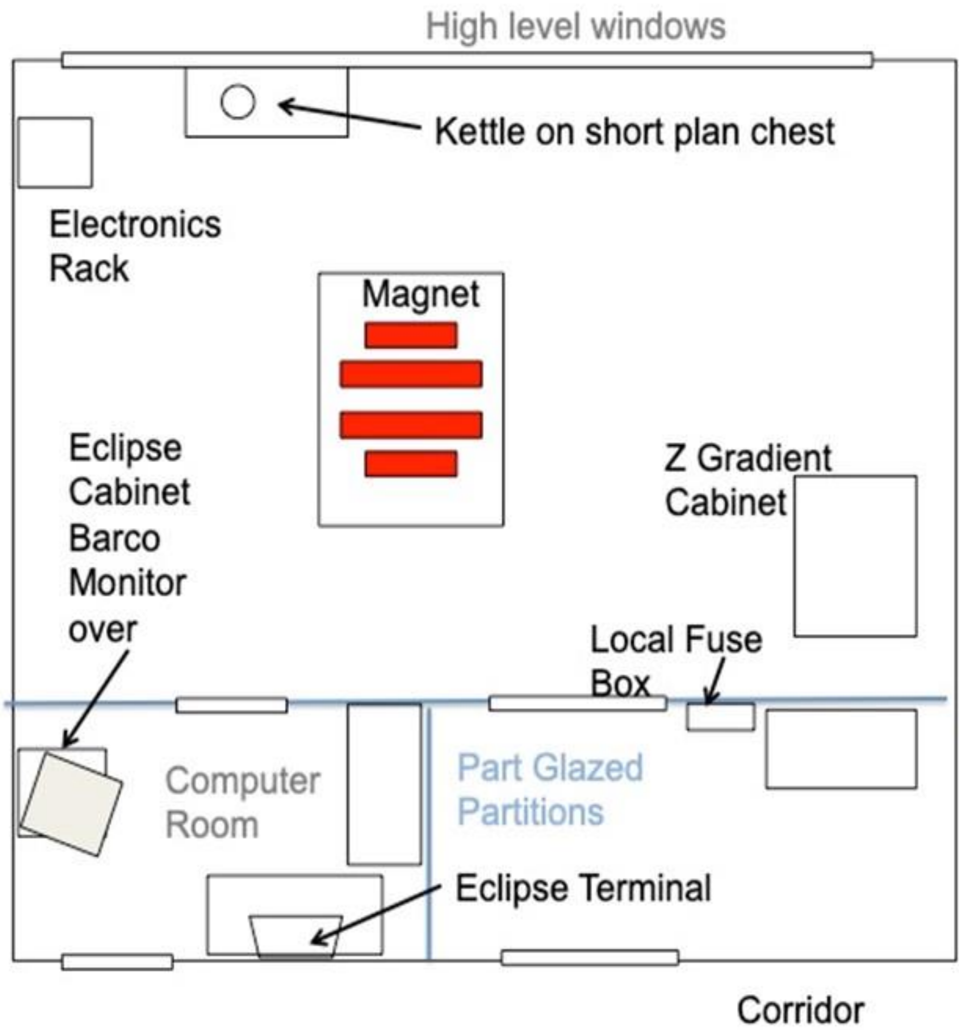
So we developed - this 'view from a spin'. I am sure that others became familiar with this and used it subsequently in considering pulse times and other scanning details.

Mike Burl developed the amplifiers and their protection of the 'front end' of the scanner. The incoming signal was taken from the signal coil, which was located inside the tube carrying the transverse gradient coils. This was no trivial task in view of the necessity of maintaining the SNR in a relatively inhospitable RF environment. For example there would be a high power RF burst at 4.26 MHz fractions of a second before the signal was to be gathered in a band centred upon that frequency. Mike has carried on in that area since, and invented numerous better signal coil geometries.

9. The build

The development work continued with pieces of hardware being integrated into the machine. This process exposed holes in our knowledge and the design. For example the transverse gradient system (mentioned above).

By now the NMR lab was beginning to take shape, in what was previously known as Hypok Hall.



9.1. The gradients

The z gradient circuitry with transformers, capacitors and switches lived in a huge grey steel cabinet in the right hand corner of the main lab close to the corridor. [Recall the thyristor bridges across the mains supply.] During design and construction the issue of protection circuits arose. The cost of fast acting high current fuses ruled them out. So a manual solution was adopted. A power relay which fed the circuits which could be dropped out by punching the big red button high up on the front of the cabinet.

One day when one of the colleagues was commissioning the z drive circuitry a thunderstorm broke out inside the cabinet, the electronics man bashed the big red button and …..

The thunderstorm carried on '*crack, buzz, flash, sizzle*…..' - oops!

What seemed like minutes later the lights went out and the thunderstorm abated. - much relief all round.

The power in our section of the Hypok block had gone out - actually a humungous great cartridge fuse in the intake cupboard at the end of the Hypok building had saved the day. The next thing up the line was the main switchboard of the EMI site Power station in Blyth Road. A round of sweet tea was in order. [Eric took his kettle to the main building to get power]

On another occasion when the z gradients were being tested - a snap snap spark noise was heard. Immediate investigation revealed that the DC power cables to the magnet had been disconnected and the z gradient and Magnet coil system was behaving as a 2 ton Tesla coil with sparks jumping across the air gap between the magnet power terminals. The test was terminated rather rapidly .

10. Further progress

In the image reconstruction area there were gaps in our knowledge and experience of Fourier Transforms. Iterative steps in this process which took several weeks in the summer of 1978 are illustrated in signal pictures below.

We were making our way slowly through the reconstruction process with limited knowledge. Some of our gaps were

* What was the meaning of the 'zeroth' value of the imaginary part of the signal, or of a signal in negative time?

* What should the signal from a complex phantom look like

* The Radon Transform and the Sinogram of its signal

The day was approaching when a brave volunteer would be exposed to the machine from the patient's position - Lying on a blockboard plank supported by a number of blue plastic milk crates which Eric had acquired as they had good electromagnetic properties.
[The plank bore the number 6.626×10^{-34}]

We were quite concerned that in stepping into this new magnetic and RF world there could be undiscovered Health and Safety issues. We had engaged an expert - Dr Ken Woolas a GP from Cosham Hants. Ken was an RF safety consultant for the DERA radar activities at Admiralty Surface Weapons Establishment on nearby Portsdown Hill. Ken used visit us fairly frequently. He was an enthusiastic active GP and we used to chat together – perhaps my Radiographic past opened wider communication. - I recall him telling me on one occasion how he had saved a patient's life when he spot diagnosed a large aortic aneurism, and sent the man immediately to a private surgeon and a longer life. Ken used to wear a particular aftershave, so on passing through reception there would be little doubt that he was on site.

We had determined a safety protocol - signed off by Mr W.E. Ingham the research director.

The protocol involved medical surveillance by Dr Woolas. This included EEG tracing being taken of volunteers and controls. Two of us (Hugh and I) had been to Atkinson Morley Hospital and had EEGs done - Hugh was to be the patient, whilst I was to provide a control. Ken Woolas was going to be present and examine both of us both before and after imaging Hugh.

Then one lunchtime Eric wanted a cup of tea to go with his sandwiches, so he went to the magnet room, where the kettle 'lived', to find the doors locked against him. It turned out that without saying anything to Hugh or the magnetics people Ian Young and some of his men had taken the magnet room over and were trying to take a head picture of Ian.

I viewed this as an act of extreme treachery and tried to complain to management about the action in particular the omission of any Health and Safety considerations.

Ian and I had a vocal row in Ted Williams' office (Ted had replaced Sid Webley on his retirement) but nothing came of it. I rarely spoke to Ian afterwards until I saw him sitting at the back at Godfrey Hounsfield's memorial service in St Clement Danes in 2004. We eventually buried the hatchet over lunch at Imperial a few years before Ian died

I still cannot decide whether Ian took it upon himself to try for a picture, or whether he was directed to do so by Ingham.

This action was extremely sad as it effectively destroyed the trust and cohesion of the team.

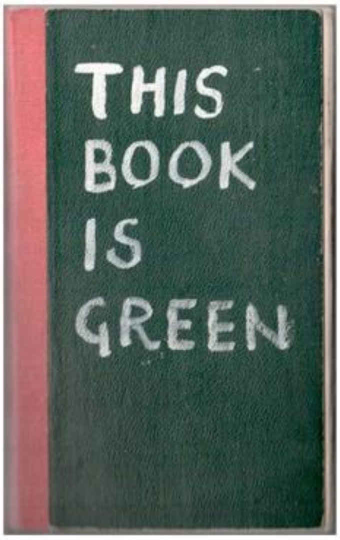
But the job had to go on.

11. Optimising the data collection and processing using phantoms

We were teaching the machine how to operate or more likely it was teaching us. - This meant tuning the various parts to perform their tasks and to communicate with each other.

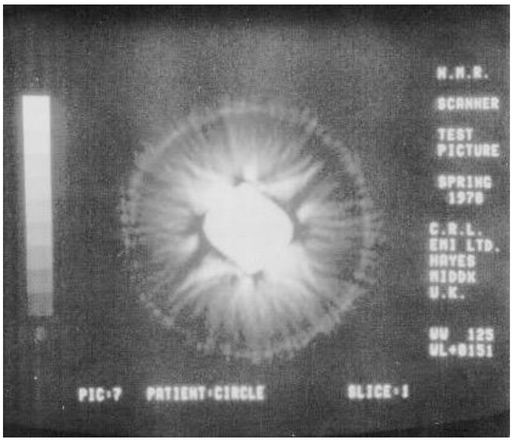
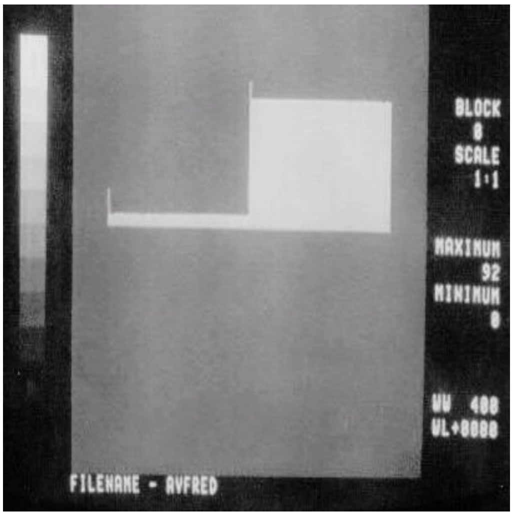
From the signal capture and reconstruction view we were collecting data and then attempting to process it, something that we had not done before. We used a photographic display monitor with its polaroid camera to make visible records of our progress. This section includes copies of some of those polaroids.

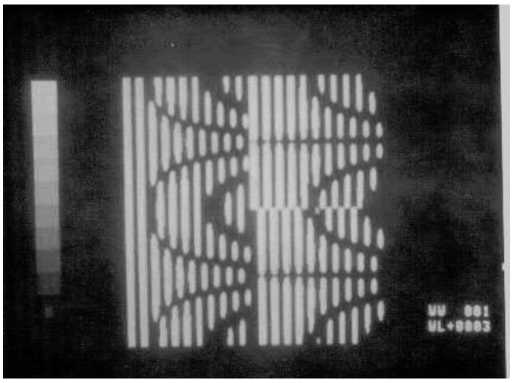
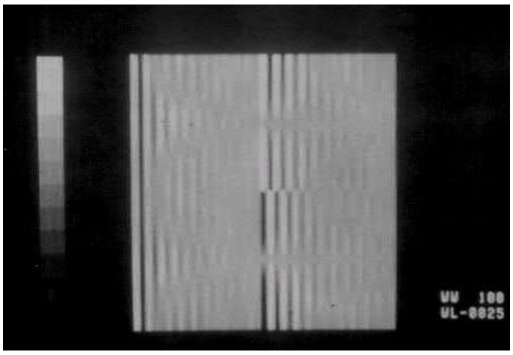
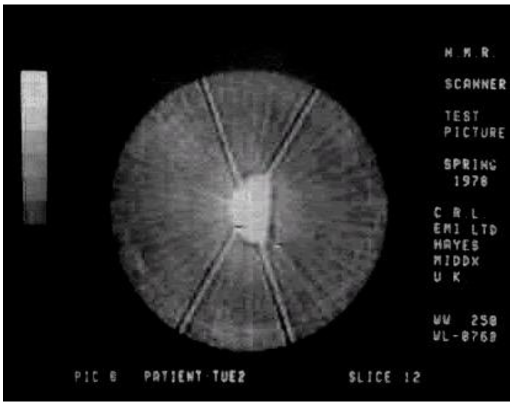
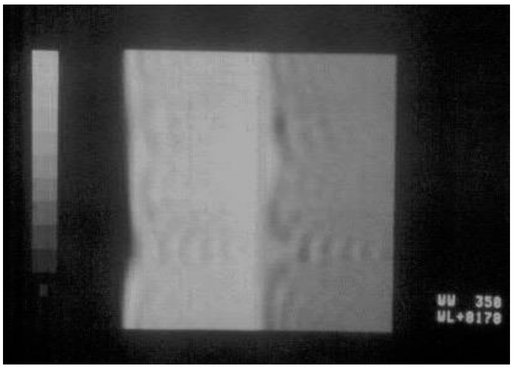
These images were stuck into an A6 notebook with Green covers from EMI stationery stores. These came in different colours, a red one was used for petty cash records. One of our team was Red/Green colour blind, so the book acquired a suitable name.

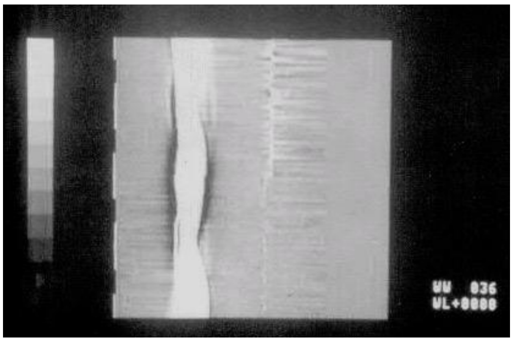
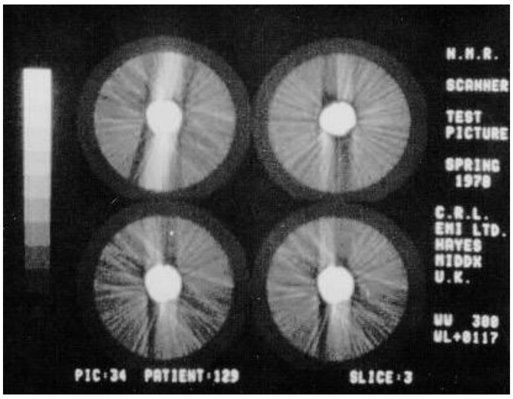
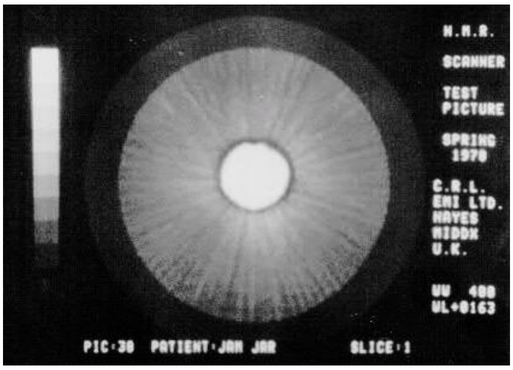
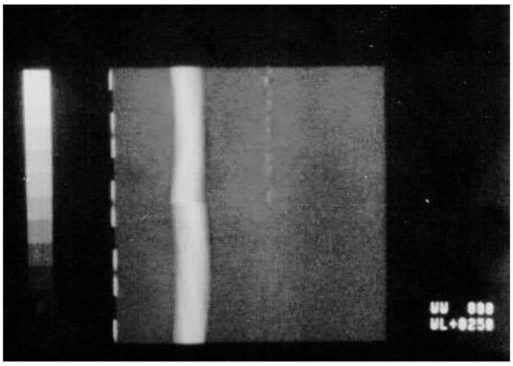


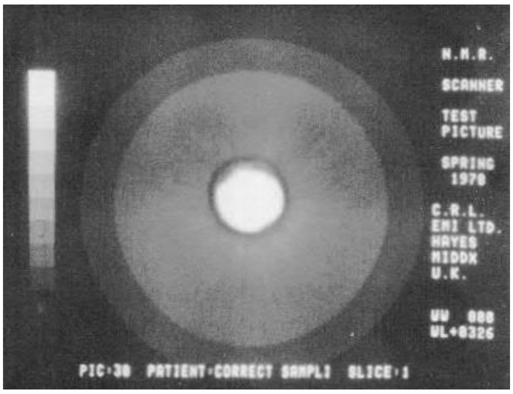
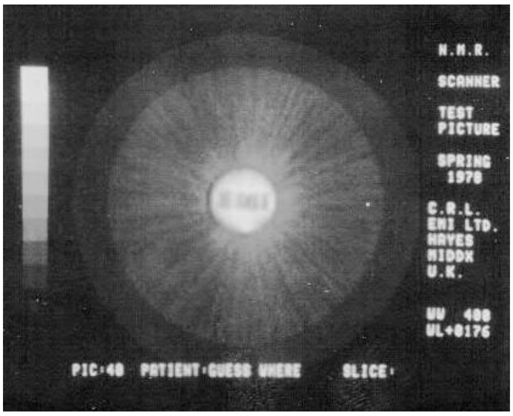
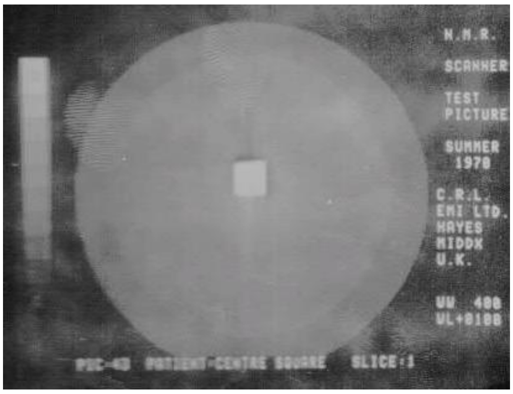
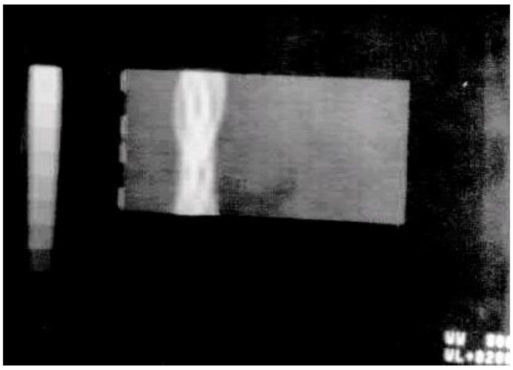
The Green Book

Copies of images saved in the Green Book, showing gradual progress in setting the machine to work, are shown on the following pages.

13 June 1978 Reconstruction is confused about angles of gradient	
13 June 1978 Input data table – The ‘old’ software error: two sides of the data interface don’t agree on the address of the first element.	

<table>
<tr><td>16 June 1978
In odd moments I had written a FORTRAN routine to generate ‘perfect’ signals. This of a non-central circular object</td><td>
</td></tr>
<tr><td>16 June 1978
Fourier Transform of ‘perfect’ signals</td><td>
</td></tr>
<tr><td>21 June 1978
Circular phantom partly filled with water. Note 90° Rotation of image, low contrast of display, and angular variability</td><td>
</td></tr>
<tr><td>23 June 1978
Raw data of partially filled phantom</td><td>
</td></tr>
</table>

23 June 1978 Transform of data above. Showing overflows	
25 June 1978 Partial reconstructions of filled phantom	
26 June 1978 Reconstruction of all data for filled phantom	
26 June 1978 FFT output of full phantom using revised sampling and correction of overflow	

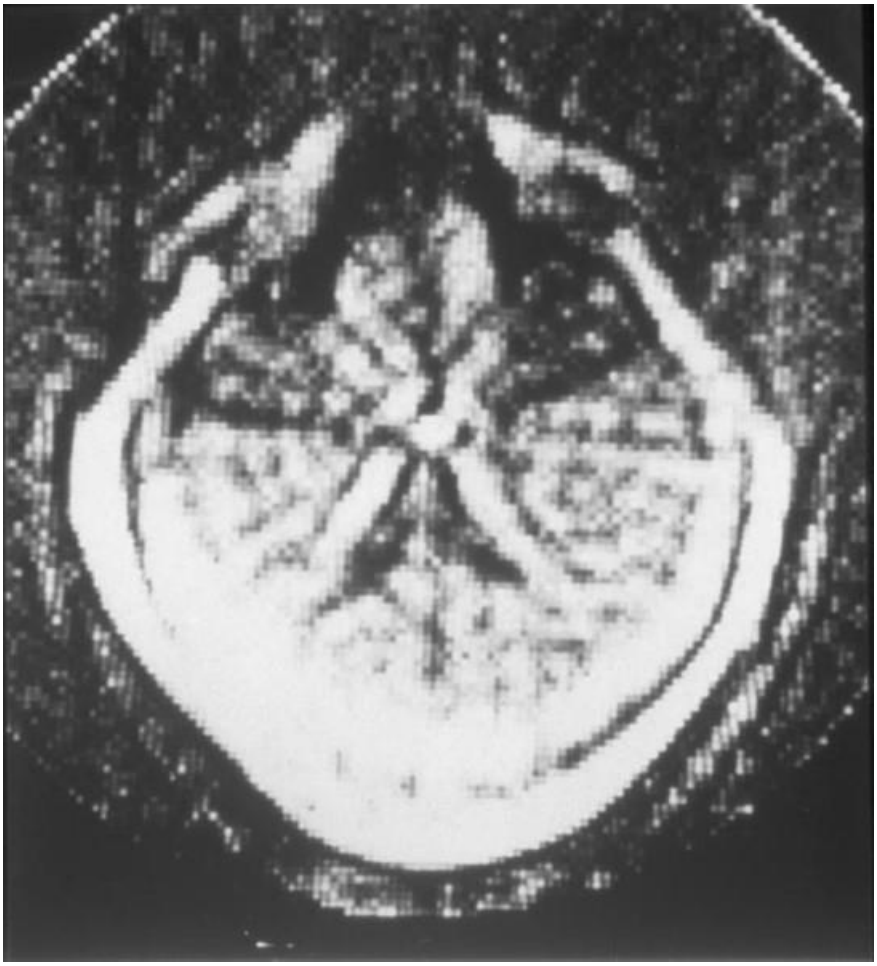
26 June 1978 reconstruction of above – Note smoother background	
26 June 1987 Guess where – the letters EMI are visible in the phantom. Eric had produced polypropyene letters which were placed in the water filled phantom	
Single square phantom	
FT of single square phantom signal [See also *Sinogram*]	

Larger EMI Phantom	

12. First scans of people

The work continued until we were getting reasonable phantom pictures it was decided that we should put Hugh in the machine on Friday afternoon 29 September 1978. We got a picture – nowhere near as sharp as those which are taken today, but showing some contrast between various tissues.

The World's first NMR Image of a living human's head



The first head picture

Dr Hugh Clow

recorded at EMI Central Research Labs,

September 1978

see "Britain brains produce first NMR scans" New Scientist 23 Nov 1978 p 588

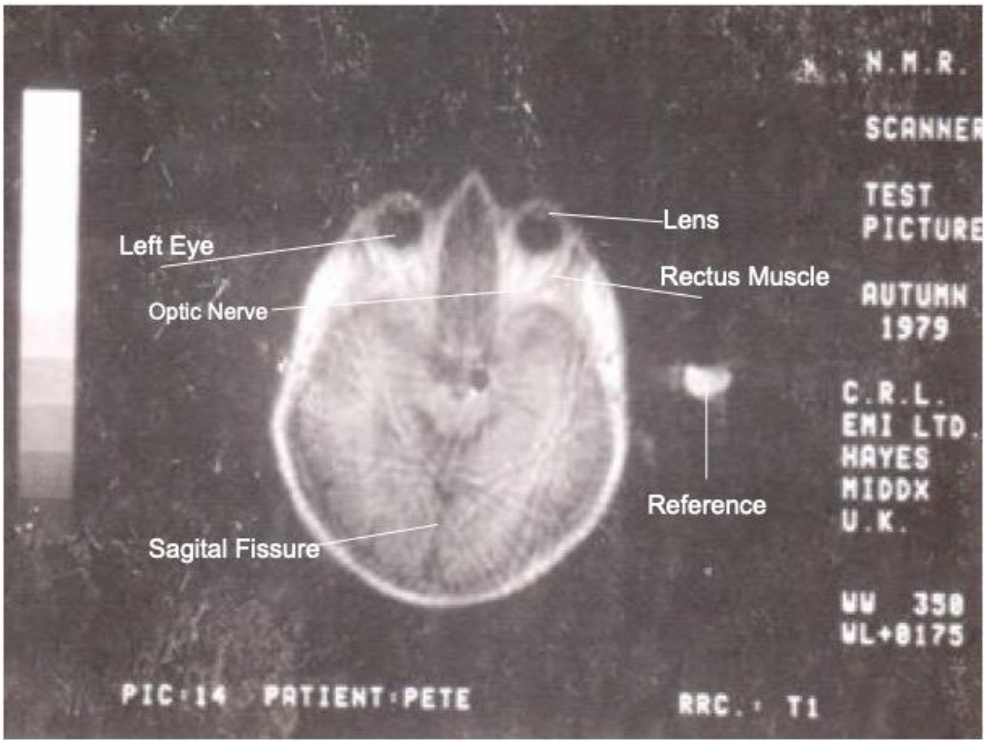
also published in The Lancet Vol 318 No 8237 11 July 1981

13. The next steps

A second image was recorded – that of Colin Harrison's head, of which I do not have a copy. Dr Woolas concluded that none of the volunteers had shown any signs of 'damage' following their imaging experience.

The first image was far from perfect, there were obvious faults: a central defect, known as The Hole in the Middle, overall noise and radial marks.

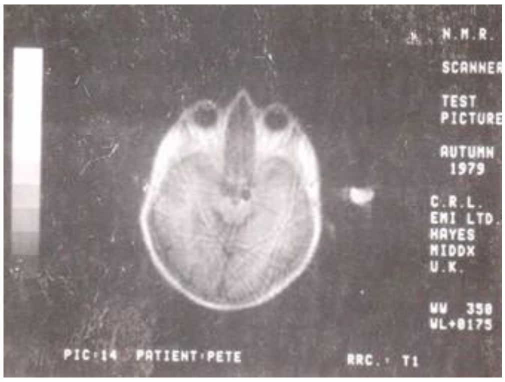
Work continued in seeking improvements in the machine, images were made of parts of various volunteers from the team and their friends within CRL. We were trying to address the obvious defects, including noise, geometric tearing and the central artifact. There was also interest in image contrast and the way in which relaxation times of different tissues affected their image. This would be important when different pulse sequences were used. Within a month or so the images were not yet perfect but clearly showed anatomical details.

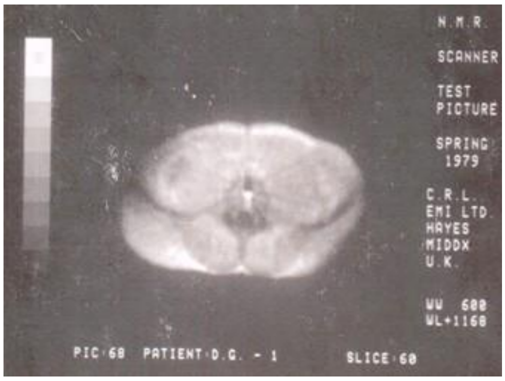


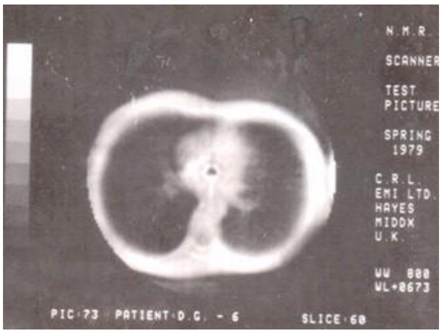
Professor Doyle from Hammersmith was keen to carry out some experimental imaging a number of rabbits which could then be examined in detail. So he and his radiographer Jackie Penock accompanied by their bunny of the day would come out to Hayes, and we did some imaging. Later in the day they would leave taking bunny with them back to the Hammersmith.

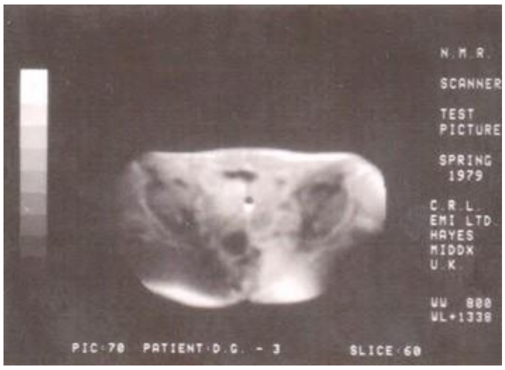
In addition there was interest in imaging the body. This had been achieved in the early x-ray head scanners by finding a slim engineer in their team – he was the mechanical designer Tony Williams. In our case it turned out that one of Ian's men had slim hips, and was keen to volunteer. So the first set of NMR body images were recorded with Dave Gilderdale lying on the plank.

Rabbit thorax

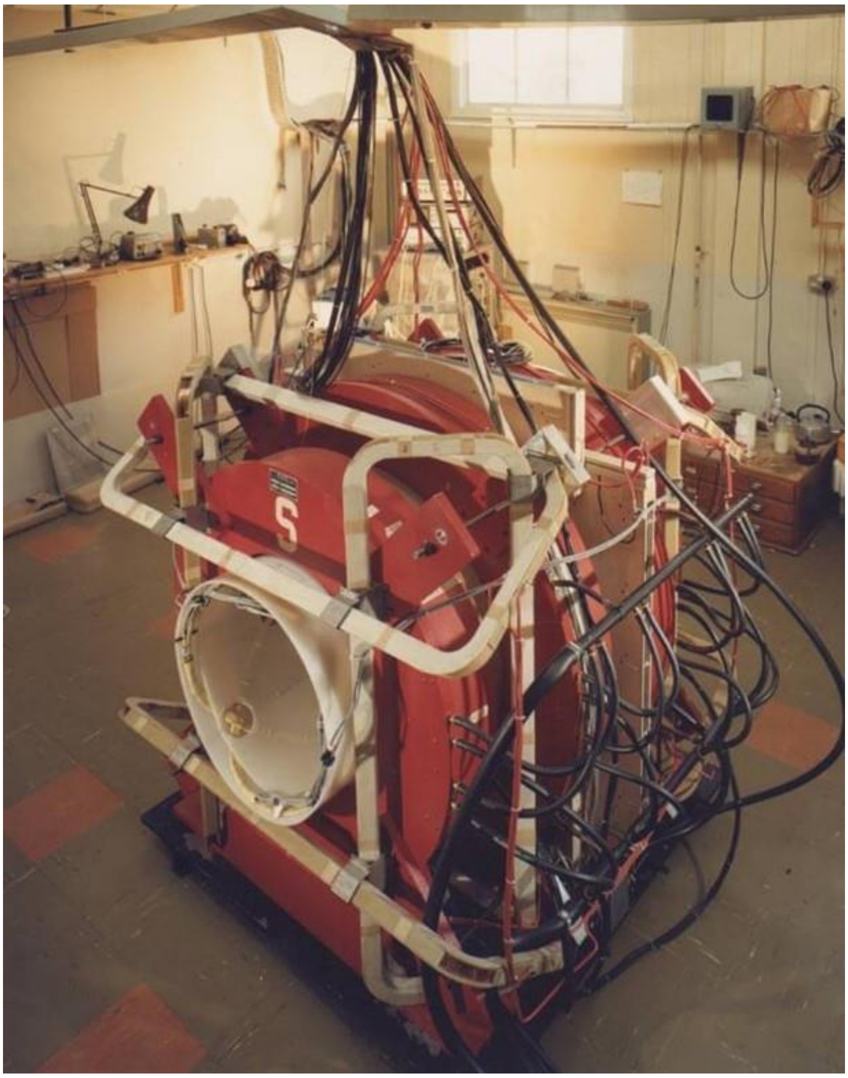








It was agreed that NMR imaging showed promise. This was supported by the ongoing experiments addressing defects, and the formulation of plans for the construction of a prototype machine 'Neptune" to be used for clinical tests. The development of Neptune is described in the MRIS book.



The Experimental Machine

Reorganisations in CRL divided the NMR team into two parts. One led by Ian Young, who took over the imaging project, whilst Hugh, and other members of his staff were to continue with theoretical studies. There was little communication between the groups. In my view this was a management inspired tragedy.

We managed to raise some funding from BTG for research into the possible use of MRI in borehole logging following from a casual conversation in the bar at The Questors with Steve Shedlock who worked at The Hydraulics Research Station Wallingford,. I was involved in some of the early work, and in communication with Jasper Jackson of LANSL (Los Alamos) who was interested in the same topic. Percival and Reg Willard worked on the development of an experimental rig, which was transferred to Wallingford for trials, but in the end it came to nought.

Ian and his MRI team built a prototype machine 'NEPTUNE' based upon a 0.3T superconducting magnet in an adjacent section of the Hypok building. This was later transferred to a special facility at Hammersmith Hospital under the control of Professor Steiner.

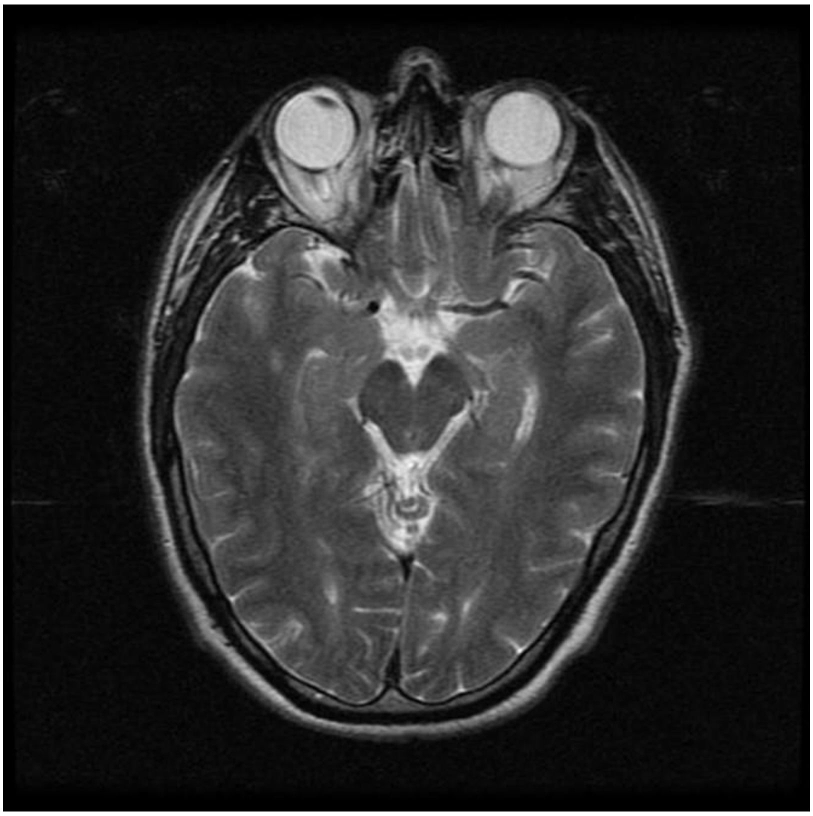
Ken Woolas died some years later of an Aortic Aneurism.

14. Conclusion

Our project came to an end. We had achieved:

- Solution of a number of new problems
- The start of an understanding of NMR imaging of the human body
- The world's first image of a human head,

But there was a huge amount of work left to be done before high quality images were obtained:



In the intervening 40+ years MRI machines have been built and sold in their thousands, and we have got on with our lives.

15. Appendix: early patents

A major aims of Central Research Labs was the generation of patents upon which EMI might generate new business opportunities. The CRL Scientists and Engineers would have the ideas. These would be written as 'patent queries' and passed to the EMI Patents department where expert patent writers such as Robert Kell would work to understand the ideas and their context. In the case of 'good' ones they would result in patent applications. These would be managed though the application process which could take a number of months and years. The Patent staff were expert in patentese – for example suppose you invented the bicycle and wrote down about your two wheeled invention. Like as not this would then appear in the application as a transport device with a *plurality* of wheels. You would have also invented the Tricycle!

Where an invention indicated a wide market applications would be made in a number of countries. The following is a list of patents. They are in a time oriented order.

Title	Inventor							Pub date	GB Pat #	US Pat #	About	Pri Date
	HC	WSP	PEW	IRY	CGH	MB	GJC					
Imging Systems	1		1					05/02/82	1584949	4315216	Stretched time	25/05/78
Gradient Correction System for the NMR Scanner				1	1				1584950	4300096		25/05/78
Fast Pulse Cycle for NMR Body Scanner	1	1	1					18/05/78	1584948	4254778	Pulsed recovery	25/05/78
Improvements in NMR Processing		1	1					02/11/78	2037999	4340862	Deconvolution in time domain	13/12/78
Slice Selection in an NMR Computed Axial Tomograph Scanner			1					28/02/79	2041537	4307344	RF envelope Sin5	25/01/79
Coil Arrangement Allowing Echo Operation				1				16/02/79	2052753	4339716	Coil geometry to permit π pulse	23/05/79
Pulsed Field System for NMR	1			1	1	1		13/04/78	2027208	4284950	Probes measure non uniformity for correction	05/08/79
A design for transmitter and receive coils in an NMR Imaging System				1		1	1	08/05/79	2056086	4362993	Orthogonal RF coils	01/08/79
Improvements to the echo Planar method of NMR Imaging.				1		1		13/06/79	2056078	4355282	Stepped gradient fields to enable 2D FT	03/08/79
Pulsed Generation of Gradient Pulsed for the NMR System				1	1			06/02/78	2056079	4384255	Following stretched time	10/08/79
NMR System Based on frequency rather than Field Slice Selection				1				03/04/78	2056081	4379262	A scan handheld	10/08/79
An Improvement into Nuclear Magnetic Logging Equipment		1	1			1		15/6/79 Addition 21/6/79	2056082		Ferrite in coil	09/06/83

Inventors: HC – Hugh Clow, WSP – Dr Percival, PEW – Peter Walters, IRY – Ian Young, CGH Colin Harrison, MB – Mike Burl, GJC – Graham Clark

CRL Patents on NMR