MRI25, P. Antell, R. Jobson, and D. Woods, Editors. 2006, Faircount Ltd.: London. p. 56-65.

An American physicist in Aberdeen: good enough engineering

By William A. Edelstein

Prologue: Harvard and Glasgow

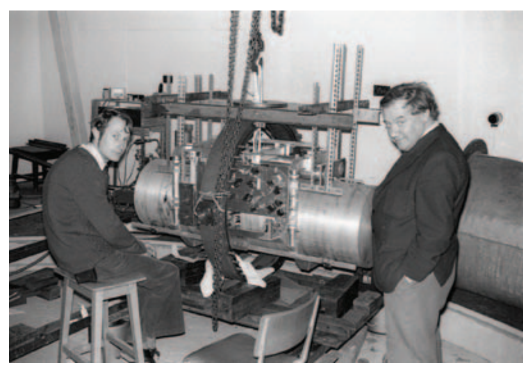
Following an undergraduate BS from the University of Illinois, my graduate career at Harvard was not the most distinguished – it took nine years to finish my PhD However, I learned a lot from my advisor, Robert Pound, a member of the Harvard team that first carried out NMR in condensed matter; from Norman Ramsey, in whose hydrogen maser lab I worked for one year; and from my fellow graduate students, some of whom were doing NMR.

My thesis work was in the general area of low-energy nuclear physics. I did experiments with a short-lived mercury isotope (44 minute half-life). My sample had to be activated in the MIT research reactor and then conveyed across Cambridge to Harvard as quickly as possible to put into my measuring apparatus. (Bicycle transport was fastest, riding in Pound's Rolls Royce was the most elegant.) By looking at the correlation between two nuclear gamma rays emitted in cascade, we could infer properties of the interaction between the mercury nucleus and surrounding electric fields, and this was related to other magnetic resonance measurements.

I was headed to the finish in the Spring of 1974 with no good job prospects. I had one interview for a potential postdoc with a low-energy nuclear physics group at Johns Hopkins and another at a small liberal arts college in Wisconsin. I was not offered either job, and I wasn't enthusiastic about nuclear physics anyway.

At some point Ron Drever, who had helped Bob Pound in his celebrated gravitational red shift experiment, came from Glasgow University for a visit. Apparently they discussed the fact that I was looking for something to do. Ron talked to me about joining his group looking for gravitational waves. That sounded interesting, so I accepted, despite some negative advice from friends, such as Scotland is a good place to be from (not go to), and that I would never make it back to the States.

Left: Glasgow University Natural Philosophy Department staff picture of WAE.



Below: Dr. Jim Hough and Professor Ron Drever with laser-equipped gravitational wave detector.

I set off for the UK in April '74 about a day before my work permit would have been invalidated. I spent a very happy three and a half years in the Department of Natural Philosophy (alias physics) in Glasgow, helping to develop concepts and instrumentation related to the laser interferometric approach to gravitational wave detection that would become LIGO, climbing Scottish mountains (known locally as "hill walking"), playing golf (I once broke 100) and making great friends. I was excited and impressed by the Glasgow group's ingenuity in making difficult measurements and producing delicate pieces of apparatus with simple materials. I learned a lot about moderate-scale engineering, which would turn out to be invaluable for building MRI systems.

1977 rolled around – time to find another job. A complication was that I had met a very nice young woman, Fiona Jones, in my bedsit building and we were about to get married in July.

Fiona Jones and WAE in front of 14 Huntly Gardens, Glasgow.

I was again unsuccessful in getting jobs in the US. I noticed a posting in the Glasgow Natural Philosophy department for a Research Fellowship (postdoc) at the University of Aberdeen Department of Biomedical Physics and Bioengineering working on an imaging project related to NMR. (This Department was part of the Aberdeen Royal Infirmary, a huge hospital complex in Aberdeen.) I probably wouldn't have done anything about it if not for reinforcement by friends who also saw the advertisement. I decided to apply, since I was now 33 years old, and it was time to look for a way to make a living.

I traveled northeast to Aberdeen by train and met John Mallard, Professor and Department head, and Jim Hutchison, a Lecturer. They had obtained a grant from the Medical Research Council (MRC) to construct an NMR imager, and that would support me as a postdoc as well as pay the project expenses.

They described the project to me. I was able to discuss NMR rationally because of my Harvard experience. The other candidates that day were a general medical physicist and a technician. I don't know if they interviewed anyone else, but within a short time I was offered the job. I doubt that I would have been hired in America, since I didn't really have NMR experience and there would have been dozens of applicants who did. Aberdeen is remote even for most Brits, so I suspect that cut down the potential pool from the UK.

I did not do any calculations or examine the literature regarding NMR imaging, so I had no idea whether it would work. I later learned that, at that time, most NMR experts had dismissed the idea as completely impractical. My thought was that even if the imaging project did not work out, I could perhaps be a medical physicist in hospitals.

Aberdeen

Fiona and I arrived in Aberdeen in September, 1977, and temporarily rented a flat on Rosemount Terrace. A few months later we bought a house on Orchard Road which was a slice of a terrace. The house had two sitting rooms and a small kitchen on the ground floor, three bedrooms (one of them very small) and a bathroom on the second floor, and a nicely finished attic that could also be used as living accommodation. There was a small front garden and a rather larger one in the back where Brussels sprouts grew explosively and parsnips failed. An Aberdeen friend told us that his uncle had spent his entire life trying in vain to grow parsnips.

The Orchard Road house (our slice of the terrace).

Fiona, an educational psychologist, took a job at a child guidance clinic in Aberdeen. Her rounds included visits to an American school where the children were somewhat out of control, but friendly. That school did not have a great reputation compared to the Scottish schools.

The NMR imaging system in the Medical Physics Department was to be built around a four-coil, air-core electromagnet with a vertical magnetic field. Each winding consisted of many turns of rectangular cross-section wire on aluminum winding forms with a c-shaped profile. We called the winding forms "bobbins." There was a motor generator that produced DC and was powered by 440 V three-phase input. The resulting voltage was poorly regulated and we would have to make our own high stability series regulator. The imaging subject was to be inserted horizontally between the two large middle windings into a cylinder which would have two of the gradient windings and the body radiofrequency (rf) coil. We called the vertical axis the "y" direction. "z" was directed along the axis of the patient, and "x" was horizontal across the patient.

Jim Hutchison standing beside the 4-coil, air-core electromagnet (September '77). Each of the coils has many turns of wire wound on the black "bobbins" visible in the picture. These are closed on the inside, open to the outside and have a "C" cross-section.

Jim had originally intended to run the magnet at 300 gauss. However, he realized that the corresponding NMR frequency, 1275 kHz, would land in the middle of the AM radio band (Brit: "medium wave") and decided that we should operate above the AM band at 400 gauss (1700 kHz) instead to avoid possible interference from radio broadcast signals.

Power dissipation is proportional to the square of the field strength, i.e. $(400 \text{ gauss}/300 \text{ gauss})^2 = 1.8$. Thus raising the field to 400 gauss would nearly double the magnet heating, and Jim had already told me that the magnet had no means of cooling and would overheat even at 300 gauss. We ramped up the magnet with the motor generator and it became too hot to touch in less than an hour. This was obviously a problem.

Most of the electronics was built from scratch. We would work on this over the next year and a half.

I started with two projects: build the magnet power regulator and make the rf body coil.

To reach 400 gauss, the magnet needed about 40 A at 200 volts (just over 8 kW), depending on temperature. Jim sketched the design of the power regulator circuit, which I then further developed and built. The output stage consisted of a pass bank of ten power transistors in parallel which would be run in series with the motor generator. This carried a total of about 40 A at a nominal 10 V. So each transistor dissipated approximately 40 W. The voltage across a series shunt consisting of a low temperature coefficient wire (manganin in a paint can) in series with the magnet was monitored and fed it back to the control circuit. Jim constructed a small NMR probe that we would use to provide the final fine magnet stabilization.

I had also been working on the body rf coil that was wrapped around the outside of the gradient form. This contained the X and Y gradients, which I had helped Jim to construct. The body coil consisted of two five-turn coils made from 8 mm OD copper plumbing tubing. The idea was to separate them by approximately the coil radius ("Helmholtz" separation). The actual spacing was adjusted to give the best rf field uniformity as measured by a small rf coil probe. Outside the magnet, the coil Q was 600 empty and 400 with Jim inside. The small Q decrease meant that a lot of electrical noise (that would compete with the signal) would be coming from the rf coil and would be adding to noise coming from the subject.

A support for the coil form was made from two inch by four inch wooden boards that would be fastened to the magnet coil forms and wedge blocks attached to the boards to support and adjust the coil position. This was completed in November.

The regulator and NMR stabilizer was also ready in November and we tried powering up the magnet. This could only be done for a limited time, since the electrical resistance of the magnet increased as it heated up. With the magnet at room temperature, we were able to put the 40A current required to produce 400 gauss through the magnet with 180 V. Within an hour, however, the required voltage passed the motor generator maximum of 219 volts.

While trying out the motor generator, a serious problem emerged. It became apparent that there was an intermittent short circuit somewhere in the magnet that caused jumps in the field. This was initially seen with the NMR probe. By making careful measurements of magnet resistance for different windings as a function of time, we narrowed the problem down to the lower large coil, and sent it back to Oxford for repair.

Fiona and I joined the Aberdeen Choral Society which was going to sing Handel's Messiah at Christmas. Many choir members had been doing this for the past thirty years or more. This did not necessarily mean that they knew the music well, but they thought they did. Some of the older men addressed each other with a cordial formality. "Mr. Jones, do you remember when the piano was positioned in the middle of the choir?" "Oh no, Mr. Smith, it was always at the front." We managed to get through the music and thoroughly enjoyed ourselves.

I also joined the Aberdeen Camera Club to follow my hobby of photography and spent many happy hours printing black and white photographs in the club darkroom. This was located on the second floor in a building in the middle of downtown Aberdeen and was quite isolated. Fiona was worried that I would get mugged, which didn't happen. The club had a meeting every month where members submitted photos for competitions in Beginner, Intermediate and Advanced categories. These would be put on a bus to a club in a nearby town, where they were judged and returned. Their commentary was read out or played on a cassette tape. I submitted my offerings to the "Advanced" section. My artistic sense did not put me at the top of the heap, but nevertheless my photographic skills advanced considerably.

While waiting for the magnet coil to return, Jim suggested we try making an earth's field NMR device to measure NMR parameters of babies. This entailed winding hundreds of turns on a cylinder in order to get inductance appropriate to do NMR at 2 kHz. We did make it work a bit (on a bottle of water, not a baby) but this was eventually abandoned in favor of the human full size project.

The experience with powering up the magnet reemphasized the need for cooling. I had several conversations with Oxford Instruments about this problem, and asked if they could make something to deal with it. No, they could not make anything to cool it and they had no suggestions for fixing the problem. They blamed Aberdeen for this obvious engineering lapse, and Jim blamed Oxford. Whatever the cause, we would have to fix it.

We received the coil back in March '78 and reassembled the magnet. I designed roughly trapezoidal cooling plates with rectangular chambers underneath that would clamp on to the magnet winding form faces. Water would be fed into the chambers via holes drilled in the plates chambers in contact with the winding forms. My thought was to have these machined from solid aluminum plates. The workshop head took the drawing and returned many weeks later with one that he had had cast. We clamped it onto one of the winding forms, pressurized it with water, and were taken aback when water came right through the supposedly solid part of plate. This told us two things: first, don't cast these plates, because they are porous; and second, we need to waterproof the magnet winding forms in any cooling scheme, since they were also made of cast aluminum.

I found some two-component liquid epoxy paint from a company on the charmingly-named Froghall Terrace and coated the magnet faces to protect them. We ran the magnet after painting until it was fairly warm, which helped cure the epoxy.

At full pressure, we were pushing water through the cooling system at 10 liters/minute, and the voltage stabilized at 216.5 V, perilously close to the supply maximum

I designed simplified cooling plates in April, rectangular with a circular depression underneath plus two holes through the plate for water input and output. The plates were slightly larger than the width of the winding forms, and screw rods, threaded through holes in the four corners of each plate, were used to clamp a pair of plates onto the form. An O-ring was made that just fitted into the circular depression and would make the seal.

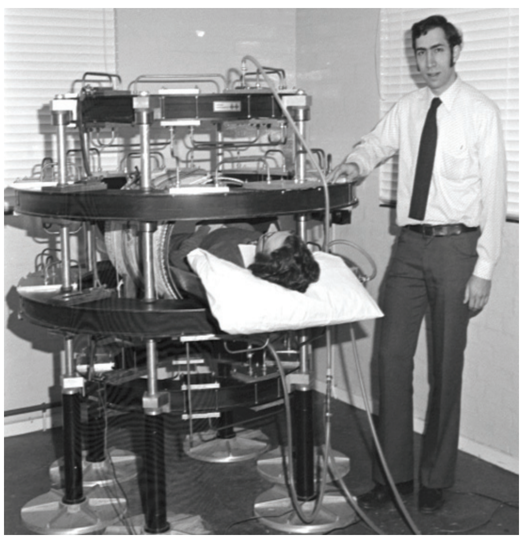
Following a lot of discussion and measurements with a single plate, we had these made in the Department machine shop. The cooling system was finally completed in late August '78. We assembled the cooling system consisting of about 50 of these plates and associated copper tubing. I had found a special Teflon-containing "pipe thread sealant" made by Loctite and applied them to more than 100 joints. Amazingly, all but one was watertight. At full pressure, we were pushing water through the cooling system at 10 liters/minute, and the voltage stabilized at 216.5 V, perilously close to the supply maximum of 219 V. We were now able to run continuously.

The water exiting the magnet was sent down the drain. Now any such cooling would need a very expensive recirculating/cooling system.

We had also been making many electronics building blocks of the system. These included the magnet power regulator including an NMR probe to provide ultimate magnet stability, a 1.7 MHz crystal oscillator, the experimental logic and control circuit, the gradient power supplies, a 200 watt rf transmitter, the transmit/receive switch for the rf coil, a preamplifier and demodulator/receiver.

At one point Jim decided to check the three phase input power to the motor generator. He opened up the 440 V, three-phase electrical junction box and overrode its safety interlocks. He plugged in a small, hand-held multimeter and there was an immediate almighty bang. Jim had left its function switch in the current measuring position, making the meter a short circuit and vaporizing its innards.

The imaging system was now as pictured below in September 1978. The cooling, power supply and various electronics were in place. With NMR lock, the current was stabilized to about two parts per million. We were ready to try it out.



WAE beside the magnet, Jim Hutchison lying on borrowed wooden patient tray inserted into the magnet. Water cooling plates and tubes are in place. The gradient coil form with the body rf coil are in the magnet. (September '78.)

We put a reasonable sample into the apparatus and saw – noise! Well, not exactly random noise, as there were definite external signals present. By comparing signal levels from the antenna to those from a resistor attached to the preamplifier input, we determined that the interference was 50 dB (a power factor of 100,000) above the minimum electrical thermal noise we should have. We had badly underestimated the amount of interference we would encounter. We tried some feeble efforts at shielding, such as attaching a few wires between the magnet winding coil forms. This accomplished nothing.

A few weeks earlier we had heard that Peter Mansfield's Nottingham group had put his MRI system into a screened enclosure. I remember smirking to myself, thinking that we would not need such shielding because we were above the medium wave radio band. Our result quickly wiped away the smile – we were now going to have to build a screened room. This was a new major hurdle.

Early in 1978 the hefty University of Nottingham PhD thesis of Paul Bottomley landed on Jim's desk. John Mallard was Paul's external examiner, and he had passed the tome on to Jim for comments. Paul worked in the group headed by Professor Raymond Andrew. Remarkably, Nottingham had two NMR imaging groups in the same physics department.

Also in the spring my father sent me a Popular Science article entitled "Damadian's Supermagnet." This described Raymond Damadian's one point at a time imaging technique and his apparatus. This approach did not use changing gradients and was much slower than the methods proposed by Lauterbur, Mansfield and others.

Fiona was expecting our first child in November and had stopped working in August.

The screened room would need electrically-connected conducting walls, floor, ceiling and door. The obvious thing to use was copper. But the thinnest copper sheet I could find was very expensive. We then settled on aluminum. Unfortunately, aluminum has a thin oxide layer and is difficult to solder. I did find some special aluminum solder, although this turned out to be problematic.

John Mallard agreed to hire Willie Hutcheon, a carpenter (and father of the departmental photographer, Raymond Hutcheon). Willie was a small, very tough fellow who lived on an Aberdeen farm outside town. We ordered all the pieces of wood for the frame. We had to lift up the magnet and put aluminum sheets under it in order to have a conducting floor. We also bought some flat "expanded" aluminum with holes that we placed in the middle of some aluminum panels and served as windows to let in air. Willie and I were joined by Glyn Johnson, a new graduate student who had started in September, and we started hammering together the frame and mounting aluminum sheets. We wanted to avoid iron, so we used brass nails.

I caused a minor accident by using a C-clamp to hold together parts of the frame. I had incorrectly positioned the back of the C underneath what it was holding, and it fell off and hit Willie, leaving him with a scraped and bloody hand. He wrapped himself with a rag and gamely went off to find his son. He told his son, "They say you should burn a wound." "We're not in the trenches, Dad," Raymond replied, as he washed his father's hand and put on a bandage from his first-aid kit.

The hardest thing about the screened room was electrically connecting all the aluminum sheets once they were nailed onto the wooden frame. Using a hand-held torch, we soldered over a thousand two-inch-long pieces of copper wire at one-inch intervals where the sheets met. The special solder flux produced a noxious vapor that made my lungs ache, even with the windows open. We bought a wooden door from a home builders supply, covered it with aluminum sheets, and installed bronze weather stripping around the edge to make electrical contact when the door was closed. It was held shut with bungee cords. We had to make electrical filters for the magnet power leads in order to prevent interference entering the room on these wires.

Jim Hutchison in magnet in screened room (still on the borrowed wooden patient couch) before the front of the room was installed. The four white, rectangular windings outside the magnet comprise the Z-gradient.

Our son Arthur was born on November 26 1978 at the Aberdeen Maternity Hospital, which was a few hundred yards from the Medical Physics Department. It was easy for me to go see Fiona and Arthur, and I sometimes borrowed a white lab jacket to get in outside regular visiting hours.

In the autumn of 1978 we were visited by Rowland "Red" Redington from GE Corporate Research and Development in Schenectady. Red would later hire me in 1980 and would be my boss. He had just had a huge success as the manager of research at GE leading to the GE X-ray CT product, and was looking for his next project. He told me later that Eric Ash of Imperial College had suggested that he look at our NMR imaging work and that I might be a good prospect. I told him we were going to make images by next spring ('79). He told me later that he hadn't believed me.

The screened room was completed and we were ready to go early in 1979. As we were ramping up the magnet, a new crisis appeared – we had another short circuit. I had depressing visions of taking the room apart and shipping pieces of the magnet off again for repair. This would be made harder by the fact that we had installed all the cooling plates. I did not relish the monumental task of rebuilding the screened room.

Dispirited, I walked into Jim's office to give him the bad news, and we returned to survey the situation. Jim got to work making careful voltage measurements with help from me. He soon localized the problem to a short between the winding wires and one of the magnet bobbins. We were able to make the short go away by prying open the bobbin. We then got a sturdy piece of plastic sheet and inserted it between the wires and the inside of the bobbin. The short was gone and did not reappear, so that is how we ran the magnet thereafter. Yikes!

We tried the assembled NMR electronics, and it soon became evident that the screened room had indeed gotten rid of interference and hugely improved our signal-to-noise ratio. We made rapid progress and obtained images of various water phantoms and body sections in March using a line-scan method devised by Jim.

Some time after the screened room was completed I was involved in a minor fender-bender while driving our Mini on the infamous Mounthooly Roundabout (everybody crashes there, I was told). Raymond informed me that his dad did small car repair jobs, so I arranged to take the Mini there on a weekend. Willie did a splendid job of fixing it. I had to argue vigorously to get him to accept £5 for his work. In the process, I got a nice picture of him that I submitted to the next Aberdeen Camera Club contest. This received mediocre marks because it had "duality." The judge said he wasn't sure if this was a portrait or an instruction page from a panel beating manual. Well, I tried.

Willie Hutcheon straightening the right front wing of our Mini.

There was a discussion meeting of the Royal Society in London on March 14-15, 1979, and John Mallard gave a talk entitled "In vivo n.m.r. imaging in medicine: the Aberdeen approach, both physical and biological." He discussed early NMR imaging work at Aberdeen done by Jim and others, relaxation time measurements of various tissues made in Aberdeen by Rosemary Ling and Meg Foster (Jim's wife, staff member in the Department), and showed some of our early images. I was unable to go because I had the flu.

We had to work on our NMR imaging patient support system, especially since John had told us that we would have to return the wooden tray. I designed a concave couch which we would fashion from a large block of plastic foam we had purchased. We made wooden forms with the shape that we wanted and strapped on to the ends of the foam. Jim got a variac transformer attached to a wire stretched between wooden handles, and we then cut the shape with the hot wire.

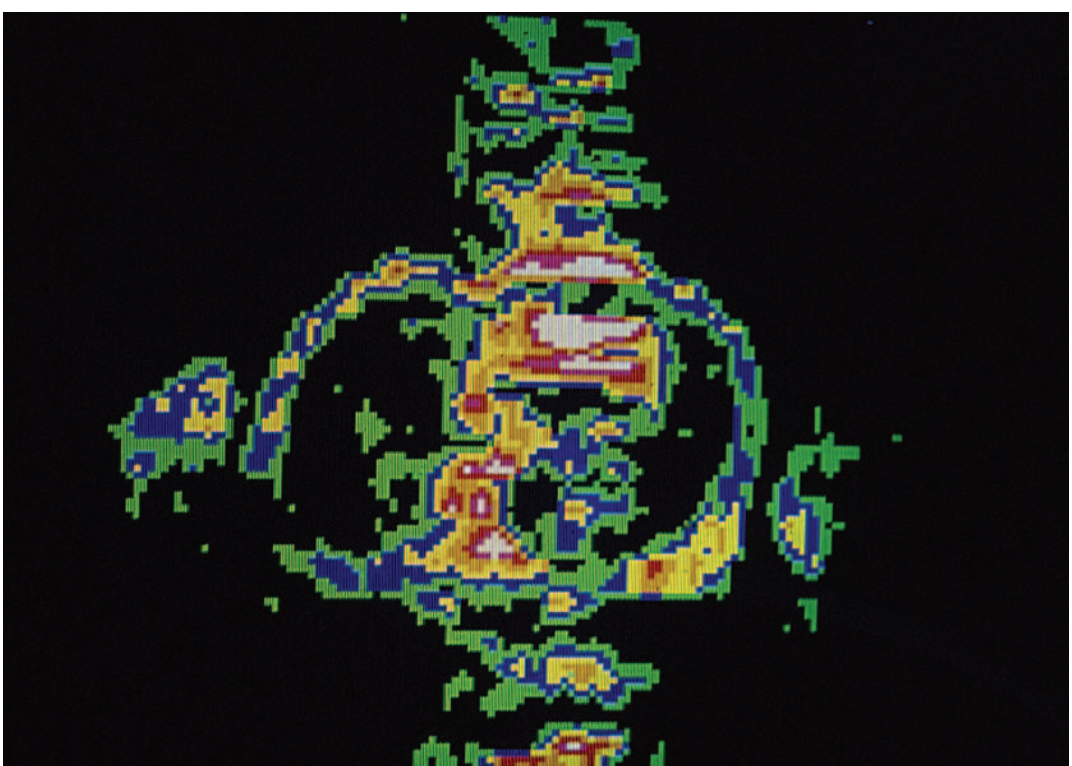
We bought fiberglass cloth to cover the couch surfaces. We discovered that the resin that was supposed to stick on the cloth dissolved the plastic foam, so we put some of our epoxy paint on the foam. We then were able to lay on the fiberglass cloth. However, the resin reaction was hot and tended to melt the foam, so we sprayed water on the whole thing to cool it off while the resin was hardening. I am sure this could have been done better!

Finally, we attached a thin piece of Formica (Brit: Melamine) laminate to the bottom of the couch and some Teflon strips under that. The whole thing slid on a long table going into the magnet, also made of Formica laminate. The laminate piece in front was attached by a hinge to the next bit, so it could be lowered and we could shut the door. The imaging subject was thus pushed in and out of the magnet by hand.

We started working on a paper describing the instrumentation, and eventually it was published in Journal of Physics E: Scientific Instruments, with the title "A Whole-Body NMR Imaging Machine." In it we described in detail the physical apparatus including the magnet, the gradient coils and rf (radio-frequency) coils; the electronics; the data processing; and system performance measurements. We showed images of a square bottle array phantom and images of Jim's chest, head and legs taken using Jim's line scan technique. We discussed why we thought that relaxation times (in this case, T1) would give more significant results, and had some image projections to illustrate how T1 images might be produced.

The chest image was, I believe, the best such at that time. However, it had a huge vertical artifact aligned with the heart. This was caused by heart motion and was a consequence of the line scan method which depended on subtracting successive signals. The lines composing this picture were horizontal. With the line scan method, contributions outside the line were supposed to subtract to zero. But since the heart changed its shape between successive signal acquisitions, signals from heart did not subtract to zero, and thus produced an image amplitude where there should be none.

Image of Jim Hutchison's heart made using line scan: heart motion between subtractive signal acquisitions causes the vertical artifact.



I briefly considered erasing the signal outside the body, since we knew it was incorrect. Of course, some of the signal within the body cavity was also an artifact. In the end, I thought it better to leave it as is. First, that was more honest. Second, I thought of golf – if you lie now, then you have to lie every time you play in order to improve your score. If you tell the truth, then it may be easier to get better. (Note: I am a lousy golfer. I am ever hopeful, however.)

I was given permission to attend an international conference on medical and biological engineering in Jerusalem in August '79. I discussed the state of our imager and other work at Aberdeen including the in vitro measurements of relaxation times.

I thoroughly enjoyed being in Israel and did many of the important tourist stops including swimming in the Dead Sea, climbing Masada, visiting the Wailing Wall and the Church of the Nativity in Bethlehem. I also looked up and met a friend I had known in high school (in suburban Chicago) who was now living in Jerusalem.

We knew that our line scan method had to be improved. Not only did it have an unacceptable artifact, but it was also inefficient, since it only gathered information one line at a time. Paul Lauterbur's projection reconstruction approach got two-dimensional information with each signal acquisition. For an image composed of 64 X 64 pixels, the projection method would get information from all 64 lines at once, and thus would be 64 times as efficient as a line scan.

Jim had not wanted to use projection reconstruction because he was concerned about the effect of motion on that process. Also, for the simplest form of projection reconstruction, it is necessary for the projections to be along straight lines. In this case, projections went along lines of constant frequency or "isochromats." Since there were significant nonlinearities in both the static and gradient magnetic fields, the projecting lines certainly wouldn't be straight.

Beginning in September '79 we were joined by a new graduate student, Tom Redpath. Tom came to me with a paper by Peter Mansfield and others on their fast EPI (echo-planar imaging) method and asked if I could explain it. Certainly, I said, off the cuff. Studying it more closely, however, it appeared to me that having the gradient perpendicular to the initial projecting direction on for long intervals would not work as it was intended. I thought of applying that secondary gradient in small pulses. This later became known as "blipped" EPI where the blips were the finite length pulses of the second gradient.

Getting a series of spin echoes from a single NMR pulse train and gathering information from all of them to assemble into an image seemed a daunting task, and it occurred to me that we could make an image using the first blip if we had different blip amplitudes for each signal acquisition. This would be a true 2-D imaging method with the same efficiency as the original projection reconstruction approach.

I talked this over with Jim, who was thinking of trying a new line scan method he had devised. After some discussion, he agreed to work on my 2-D method. We now had to make a new amplifier that would be able to produce a series of gradient blips with controlled, changing amplitudes. Following some work on amplifier design, I bought a hi-fi audio amplifier circuit board and modified it so that it would operate as a voltage-controlled current supply. Jim made the necessary changes to the hardware experiment controller.

Arthur was thriving. He was now about a year old. However, at that point he did not walk or even crawl. Apparently there is a percentage of babies that are "bottom shufflers" who end up walking fairly late – he started at 20 months. This was easy on Fiona and me, as he would sit quietly playing in the middle of a room and not move. He liked turning pages of magazines – National Geographic was his favorite. We weren't sure if that was because of the pictures or the smell.

WAE, Arthur and Fiona in the back garden of 5, Orchard Road.

John Mallard obtained money to purchase a Hewlett-Packard regulated power supply to replace the motor generator. It still had to be put in series with our regulator circuit with the reference wire and NMR lock. The better stability of the HP supply did improve our final stability, however.

We worked to make system changes and were ready to try it out on February 21, 1980. Jim and I were there late at night and first made one or two images with a bottle. Jim then crawled in and I took an image. My notebook entry was “Jim’s heart. Wow!” It was incorrectly proportioned so that the vertical and horizontal scales were not the same. A simple rescaling of the blip voltage fixed that, and we had the best NMR body images ever.

Over the next month or so we worked on tweaking the system and took many images of ourselves. I decided that we should give our method a name and suggested “Phase Warp,” as the spin phases were twisted by the increasing blips. Also, it sounded a bit Star Trekky. Jim came back the next day and said that Meg had offered a variation, “Spin Warp.” OK, I thought, more people would know the word “spin” than the word “phase,” so Spin Warp it was.

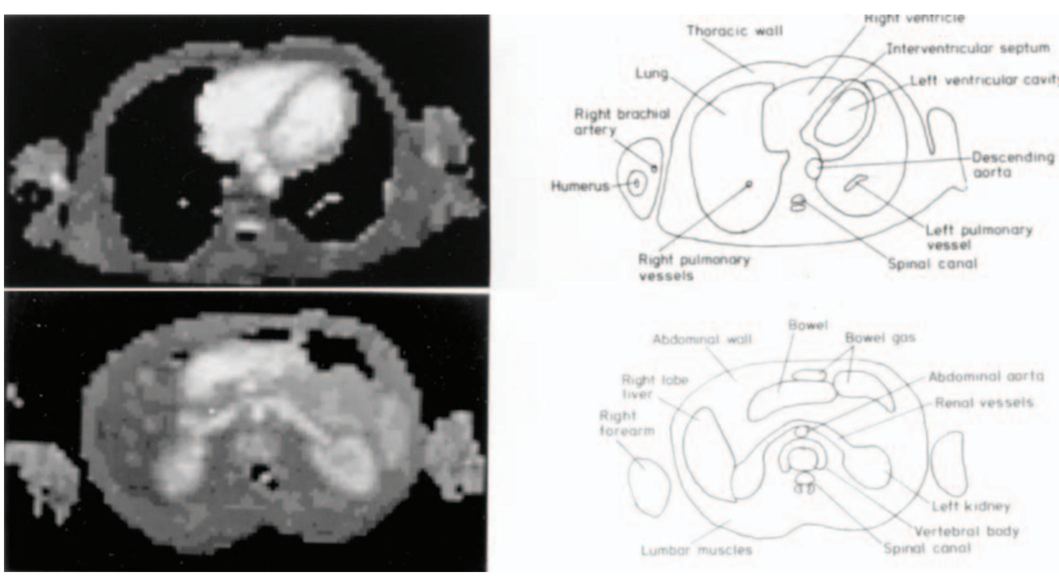
I spent weeks taking photographs of our images on a black and white monitor, trying to get the right range of gray scale shades in the pictures

We filed patents on the improved EPI sequence and Spin Warp with the National Research Development Company (NRDC), a government organization that was supposed to patent the output of UK universities. Eventually the Spin Warp patent brought tens of millions of pounds of royalties to the University of Aberdeen, and the inventors each received a substantial sum of money passed along by the University.

Jim pointed out to me that the correct antecedent to our method was “Fourier Zeugmatography” from Richard Ernst and colleagues at ETH in Zurich. The integral under the blip produced the image information in the direction perpendicular to the projection direction.

We got different integral values by having a blip for a fixed time that changed its height as we gathered successive image signals. The Ernst method changed the integral by having a blip of fixed height for different times. Our method turned out to be much better in practice. First, taking up longer times, as did the Ernst approach, would lose signal. Also, our method was substantially immune to field inhomogeneities, whereas the Ernst method was not.

I wrote a manuscript describing Spin Warp and containing imaging results. We decided to submit it to Physics in Medicine and Biology as a letter to the editor.



Spin Warp T1 images of WAE torso (from Ref. 7). Top–chest/heart image. Bottom–kidney image showing renal vessels.

Perhaps because the Department had long made nuclear images, we had been looking at our images in color. The journal would only accept black and white. I spent weeks taking photographs of our images on a black and white monitor, trying to get the right range of gray scale shades in the pictures. Jim finally said, good enough, Bill, so I quit and we sent it to the journal. It was quickly accepted and published in July, 1980, well before the previously written instrument paper which appeared in September. (The Spin Warp paper now has about 600 literature citations.) I later was convinced at GE that black and white images are the right way to go, and this is how essentially all clinical MRI is done.

John suggested that we compile a set of "normal" images and submit these to the British Journal of Radiology. Jim and I had a talk with Dr. Francis Smith, a radiologist in the hospital, and asked his advice on what to look at. "Thin man, fat woman," he replied succinctly. We couldn't get anybody too large into the machine (it had about a 10 inch vertical clearance) but we did put in a variety of people. Imaging a woman showed us that fat (with short T1) has a huge contrast with other tissues. All women have at least a thin layer of subcutaneous fat. Jim, the graduate students and I had virtually no abdominal fat at the time. We eventually wrote the BJR paper, and Frank went on to take the lead in putting the system and its successors to clinical use.

In 1980 I was able to attend meetings of the Hospital Physics Association and the British Radiofrequency Spectroscopy Group. The latter took place at Nottingham University where I was able to meet members of both the Peter Mansfield and the Raymond Andrew NMR imaging groups. I had also become aware of other UK competition such as the EMI group in London and a research effort at GEC, also in London.

My Fellowship would end in September and I had been looking for another job for some time. The Department was too authoritarian for my taste, and John Mallard found me too rebellious. He said he could perhaps get me a lectureship, but it would be doing routine hospital work and I would not be able to work on NMR imaging.

I tried, without success, for numerous jobs in the UK. One interesting experience was going to Risley for a job interview with the UK Atomic Energy Authority. I encountered there what was called a "paternoster" elevator, which might be described as a vertical escalator. I assume the name referred to a prayer you said before using it. It had open compartments that slowly went upward in one shaft and down in the other. You were supposed to step on it as it was moving. A petite secretary (at least a foot shorter than me) helped me onto it going up. I found it pretty scary, and she decided that taking the stairs was safer for both of us on the way down. I am sure it would have been fun to learn to ride it. I didn't get that job either.

I applied for university postdoctorates and faculty positions and industrial jobs in the UK. One of the latter were with GEC, the British General Electric Company, which had a project on NMR imaging. No, they said, they already had somebody in charge of their project. I didn't have to be in charge, I said, but never heard from them again. I began to wonder if the British do not like to hire Americans. I started applying in the US, and was able to arrange interviews with the Shell Development Co. in Houston (thanks to my friend Harold Vinegar), with the MIT-Harvard Health Sciences Program and with the GE Corporate R&D in Schenectady. During this trip I was also able to visit Paul Lauterbur at SUNY Stonybrook on Long Island.

MIT was interested but vague, and never came up with a concrete offer. Shell offered me a job as did GE. I decided to take the latter because it would give me a chance to continue with NMR imaging.

So, in August, Fiona, Arthur and I set off for Schenectady in the new world, with our belongings conveyed by the Shore Porters Society of Aberdeen (founded 1498). There would be a lot of exciting work to be done at GE.

"NMR Imaging" would become "MRI." The standard field would be 1.5 tesla, nearly 40 times as strong as the Aberdeen field. MRI would become a multi-billion dollar business and a medical boon for millions around the world.

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