The hard swelling did not return but the affected area eventually turned purple. Over the next few days, that discolouration spread up to the elbow, but it was not painful. It took three weeks to disperse, again starting from the wrist, and the last area to return to normal colour after turning gradually black, was the inner side of the elbow.

So what was happening? Remembering that the radial artery had been cut open, the blood flow had to be stopped to allow the wound to seal. The inflated plastic tube was doing the job of an old-fashioned tourniquet: stopping the blood flow, but with the pressure carefully monitored. Not being allowed out through the wound, blood was gradually leaking into the surrounding tissue. That is the haematoma. Any bruise, caused by any injury to the soft tissue without breaking the skin (which gives rise to the phrase ‘turned black and blue’), is basically the same thing.

To be continued . . .

What happened next gave me further experience of health care. I was given an opportunity for further involvement which would provide me with some ongoing monitoring, help the health service and provide me with further development of my own knowledge.

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Science in health care

A heartfelt experience, part 2: an explanation of MRI scanning and a patient’s experience of the process

Geoff Auty

Abstract This article describes what magnetic resonance imaging is, and how it works is explained by comparison with other topics taught in school physics. It also compares MRI and its relative safety with other imaging methods. This is followed by a description of a patient’s experience in undergoing investigation by this non-invasive method.

The morning after my heart operation, described in the first of this two-part account, a research student came to check on my progress. He also had an extra motive: he asked if I would volunteer for a follow-up MRI (magnetic resonance imaging) scan. The reason was to study the effectiveness of MRI in heart cases; as the technique was constantly being developed, images of people in my new-found situation were valuable. But it would have to be within a week – before recovery had gone too far – and would then be compared with a second scan about 3 months afterwards. Having studied the basics of MRI, seeing pictures of it happening (with the patient inserted in a tube) and hearing stories of it being very loud, I was quite apprehensive. But then I thought, ‘*The system has helped me – I must help the system – and become a “guinea pig”*.’ So I agreed. It also had the advantage of giving me the best possible follow-up check to see if there was recovery, stability or further problems.

In the media and in conversations, the term ‘MRI’ is now often used as if it is known and understood. But do people really know and understand what it means? Publicity states that it is safe and does not involve radiation. When such claims are made, the process is being compared with X-rays and gamma rays. It does involve a form of radiation, and the publicity should really state it does not involve *ionising* radiation. X-rays were initially used for body imaging to see the bones through the flesh, but prolonged exposure (to X-rays and to gamma rays) can be damaging.

Creating strong magnetic fields

MRI requires the patient to be placed in a strong magnetic field. This method relies on the fact that the body contains a vast proportion of water, and the magnetic resonance is achieved by the field acting upon the hydrogen in that water. The hydrogen-to-oxygen links are covalent bonds and, as the electrons from each hydrogen atom are strongly linked to the oxygen atom, the hydrogen atoms (while remaining within the water molecules) can behave almost like free protons (I remember my own A-level chemistry teacher saying '*Almost like a naked proton*'), and, as protons have spin, this spin tends to become aligned with any applied magnetic field.

To be successful for imaging purposes, very strong magnetic fields are needed. Permanent magnets cannot provide the required field strength so electromagnets have to be used. The magnetic flux density depends on the current and the number of turns in the coil of wire. Inspection of the motor in a model electric train or Scalextric car will show that it has extremely fine copper wire to enable many turns to be used in the available space. The current in every turn contributes to the magnetic field, offering a large field from a small current. Copper is one of the best electrical conductors, but is not perfect. In your house, thick wires are used in the power circuits (to supply the 13 A sockets in Britain – a 3 kW electric fire will take about 12 A). Thinner wire is used for the lighting circuits (a 100 W tungsten lamp takes less than 0.5 A). Resistance of metals generally increases with increasing temperature, and overheating (perhaps leading to fires) is the risk if the wire is too thin.

For the high current and many turns of wire needed to produce the strong magnetic fields in the MRI scanner, the answer to the overheating risk is to keep the system cool, *very* cool. Liquid helium is used in the cooling system as it has a boiling point of 4.2 K (that's –268 °C). Yes, almost absolute zero! Keeping the essential area so cold is one of the highest costs involved in MRI scanning.

Coils and magnetic field direction

In traditional X-ray imaging, the main contrast is between bones and soft tissue, but, using MRI, the various 'soft tissues' are distinguished by their water content. Muscle and fat are different. The different proportions of water in organs such as the heart, liver, lungs, and so on, enable them to be distinguished readily in the images obtained. Arteries and veins show up well because of the high water content in the blood. Sealed from view, the MRI scanners have coils fitted around the tube in which the patient is inserted, to provide magnetic fields, and images are compiled from information gathered by induced currents in other coils.

The geometry is more difficult for this two-dimensional arrangement on a cylinder. To begin to understand what has to be done, consider the ink-jet printer attached to a computer. The printhead tracks across the paper, producing perhaps a line of print (or a part-line if the font is large). The action of the printhead as it moves steadily across is controlled by digital signals from the computer. Usually, the paper is moved up for printing the next line. It would be more difficult to engineer but it is possible to imagine a printer in which the paper is laid flat rather than around a roller, so that the printhead would be moved down a little to print each new line. Continuing the process, a two-dimensional plot would be achieved to produce the whole page of text.

Now reverse the thinking! Instead of printing, consider using an optical detector to record the image of a printed page or a picture beneath as it passes over repeatedly, and then moves down a little to record the next area. This is what a scanner does to copy text, drawings or photographs for your computer, which you can then see on screen and print out if required. The MRI scanner effectively produces a two-dimensional image of the scanned area in a similar way. Repeated scans of slice after slice of the body-part can be obtained. Scans of the brain are now used in the search for suspected tumours. The resulting observation seems rather like buying loaf of bread and being able to inspect the quality of every slice without opening the sealed packet.

However, things have moved on from the original discovery, and full scanning in three dimensions is now achievable. A magnetic field along the axis of a tube is relatively easy to arrange. A coil is wrapped around to produce a large solenoid (Figure 1). Slimmer versions of solenoids are found in every school physics laboratory. Figures 1, 2 and 3 enable comparison of solenoids and field coils for electric motors. The ratio of length to width is not necessarily the same.

To provide fields in other directions, further coils are needed. A coil at the side, such as shown in Figure 2, together with a matching coil on the other side, will produce a magnetic field horizontally across the tube. A pair of field coils as indicated in Figure 2 will be found in many electric drills or starter-motors in cars, but they are generally wrapped in additional insulation, which prevents the individual turns being seen even when the motor is taken apart.

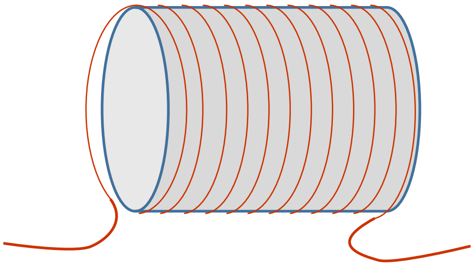

Figure 1 A solenoid – the current flowing around this cylindrical shape produces a strong magnetic field along the direction of the axis

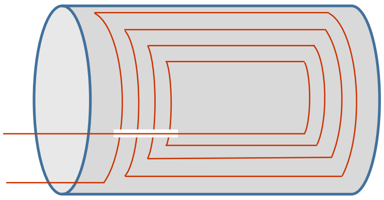

Figure 2 Illustrating one of a pair of coils that provide a magnetic field horizontally across the tube (in this view, the second coil is behind the tube)

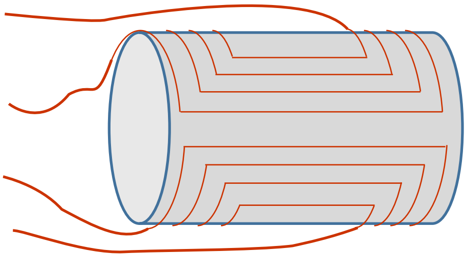

Figure 3 Illustrating coils above and below the tube to provide a magnetic field in the vertical direction

To provide the magnetic field in the vertical direction, a pair of coils like those at the sides, are positioned above and below the tube (Figure 3).

To be able to achieve a magnetic field of very large flux density requires very many turns of wire in the coils. As explained, because the system is kept extremely cold, very fine wire can be used. In fact the coils at the sides of the tube and at top and bottom can be formed on very thin sheets of plastic, like a printed circuit board (as found in most modern electronic equipment) except that, in this case, the plastic sheets are so thin and flexible that they can be formed flat and then laid around the tube during construction to form a curved (part-cylindrical) shape. Note that in order to obtain the best field pattern, the shapes of the coils are not as simple as indicated in Figures 2 and 3. Variations in shapes and the spacing between conducting parts can be arranged using a printed circuit much more easily that using insulated wire. On the flat sheet, the appropriate pattern can look rather like a fingerprint.

Plotting three-dimensional images

Having created a strong magnetic field to align the hydrogen nuclei as required, additional magnetic fields of lower field strength are used at high frequency, to create small oscillations. These additional fields are created by currents in further layers of coils. Through any length of wire, the current is of the same magnitude at all points. However, by varying the current in the extra coils, variations in field strength are produced. These are described as gradient fields, as the magnitude of the magnetic field (flux density) can be varied along the direction of the field.

With the nuclei aligned, the oscillation is rather like that of a stretched guitar string. The resonant frequency suitable for this is in the region of 64 MHz. The oscillations can become so large that the nuclei can turn through almost 90° (that's perpendicular to the original alignment). When this excitation field is switched off, the spinning nuclei move in a precessional motion (like a spinning top slowing down). This action generates a radio-frequency signal that is detected by yet more sets of coils and used to generate an image.

The excitation fields are created in three dimensions, which enables the information from the returned signals to be plotted in three-dimensional space. In this way, images of the inside of the patient can be plotted in three dimensions. This is like the chance to inspect sliced bread mentioned earlier, except that a computer plots all the images (three two-dimensional pictures in three independent directions) but the imagined loaf of bread remains uncut and sealed.

Unlike X-ray imaging, there is no screen to pick up the signal. The information must all be fed into a computer. The way this is collated is very complex.

By use of Fourier transformations, the location of any point in the space can be found by reading the frequency and recording it in the information sent to the computer to be used for displaying the image. In simple words, the location is not found by knowing x, y and z coordinates, but by knowing what frequency of modulating signal was used at those coordinates.

Once all that information is gathered, images can be recalled and displayed not just in the three basic dimensions along and across the axis of the tube, but in any plane dimensions the operator wishes to see.

Safety

Earlier I mentioned the claim that there was 'no radiation' involved. Frequency-modulated radio in Britain operates using signals in the range 87–108 MHz (described as VHF). To obtain better resolution, television moved some years ago from VHF to UHF, with frequencies ranging from 470 MHz to 890 MHz. Sodium vapour lamps (at one time almost universally used for street lighting) have a wavelength of 589 nm, giving a frequency of 5.09×10^{14} Hz, or 509×10^{6} MHz. All of these familiar and popularly used (and evidently safe) applications of electromagnetic waves have much higher frequency than that used for MRI scanning.

The range for X-rays is from approximately 3×10^{16} Hz to 3×10^{19} Hz, and gamma rays from 3×10^{19} Hz upwards (though there is some overlap because the names indicate the source rather than the frequency). As explained, X-rays and gamma rays are the dangerous ones. It seems that the claim 'no radiation' is not strictly true, but if frequency is the deciding factor, MRI operates within a safer frequency range than our lighting, radios or televisions.

Additional explanations of scanning

Physics teachers will know that in a cathode ray oscilloscope, a beam of electrons is accelerated through an anode to reach the screen, producing a fluorescent glow. This is a single spot of light on the screen until it is deflected by electric fields applied by a high potential difference (voltage) between pairs of plates at the sides and above and below the tube. Making the spot move rapidly and repeatedly at constant speed across the screen produces the impression of a steady bright line. Then, applying an alternating potential difference to the 'Y-plates', the spot moves up and down while moving across the screen and traces out a sine wave. That process keeps on being repeated and electronic control (the triggered timebase) can make the trace continue to repeat from the same starting point, putting the trace at the same place on the screen again to give a stable image.

Traditional televisions operate in a similar way, but magnetic fields are used for the deflection of the electron beam (cathode rays). Varying current in coils above and below the tube produces a vertical field that can move the spot across the screen. Coils at the sides produce a horizontal field and cause deflection downwards. Varying the brightness at each point on the screen is achieved by passing the stream of cathode rays through an additional electrode (for historic reasons called a grid), which is negative. Making that electrode very negative stops the cathode rays completely and the screen appears black. Varying its potential enables the brightness to be varied and coordinating this with the repeated movements across and down the screen builds up the picture. For colour televisions, this has to be arranged for each of the three primary colours.

The variations are rapid and coordinated so that 25 new images per second are produced – quick enough to allow motion of images to appear smooth rather than 'jerky'. These televisions were very long from front to back to allow sufficient room for the cathode ray beam to spread out and produce a large picture. Televisions were frequently placed in the corner of the room for that reason. More recent designs can be almost flat and are now sometimes mounted on a wall. They use digital signals.

Considering again the black-and-white television using cathode rays, to move the spot once across the screen requires the magnetic field to change from maximum negative to maximum positive and then return immediately to negative to enable the process to be repeated and produce the next movement.

On a 625-line analogue television, the scan starts top left and finishes in the centre of the screen at the bottom after 312.5 lines, leaving gaps between the lines. A second scan repeats the process, scanning in the gaps for another 312.5 lines, making 625 lines in total. This is called the phased alternate line (or PAL) system and the method is described as interlaced scanning. The phosphor on the screen has to fade just before a new scan arrives at the same place to enable the correct detail of the following frame to be created, so careful choice of material for the screen is needed.

At 50 frames per second, a complete new frame is created every 0.02 seconds. Hence, each full scan of the screen takes 0.01 seconds, and the time to scan a single line across the screen is $0.01 \div 312.5 = 3.2 \times 10^{-5}$ seconds. The graph in Figure 4 shows the applied potential difference against time. While tracking 312.5 lines across, the scan is also made to travel once down the screen in 0.01 seconds. A graph for that is shown in Figure 5, but not to the same scale. 312.5 peaks of the graph shown in Figure 4 occur during the time indicated in Figure 5. This constant repeating production of lines produces a steady white glow on the screen. To form a picture, a varying signal is applied to the grid, which controls

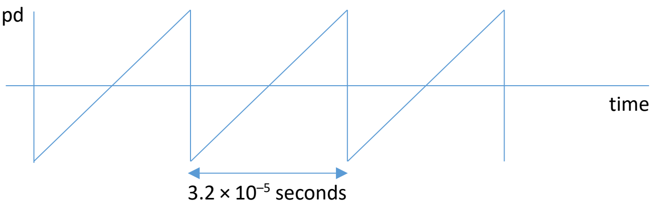

Figure 4 Graph of applied potential difference (pd) to produce a single sweep across the screen

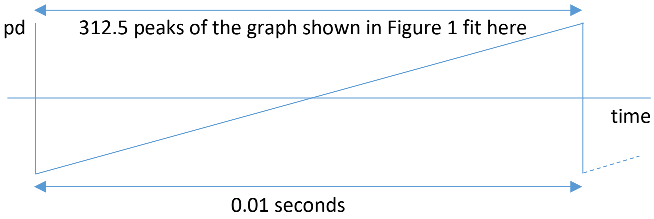

Figure 5 Illustration of applied potential difference (pd) to produce a single sweep down the screen (not to same scale as Figure 4)

the intensity of the cathode ray beam and in turn determines the brightness at every point on the screen.

The monitor used to show the image of the beating heart and the body region around it works like any modern television or computer monitor, but the electronic detail for digital screens is more complex than on the original cathode ray screens.

My experience

After signing paperwork and getting changed into hospital clothing, I laid down on the platform that could slide smoothly into the MRI machine (Figure 6). I had brought my own choice of music (soothing Viennese) on a CD, and was given headphones. Then I was pushed gently into the large ring. The music started and the one of the two operators asked if I was OK (‘*Is the music at the correct loudness?*’). I felt quite settled and was asked to keep as still as possible. I was able to communicate with the operators if needed, but I felt quite calm about things. There was a background noise once the scanner started. I do get very irritated by loud noise, but this was not so loud as to drown my gentle orchestral concert.

Figure 6 The MRI scanner in which I twice spent a ‘relaxing’ hour or so, lying on the area covered with the white sheet. The top part of the trolley could slide through the hole in the centre, taking me with it and stopping to scan the regions required. The bright blue-and-white sky above is not real, the clouds never move. The room is on the ground floor of a high building and has a false ceiling, it is probably provided as a calming influence for apprehensive patients.

As time passed, I was moved further into the scanner tube. At frequent intervals I was asked if I was all right and quite often given instructions, mostly ‘*Take a deep breath. Hold it. Breathe out. Now breathe normally.*’ In the later stages this was repeated quite rapidly, with hardly time to take an extra breath or two before I was asked to take another big one. The CD had almost reached the end of its 65-minute playing time when the platform was slid out and the job was done. Perhaps the hardest part was trying to lie absolutely still on a fairly hard surface for such a long time. However, they coped with the occasional shuffle and only once asked me to try to hold still for a few moments longer.

As I was leaving, the next ‘guinea pig’ was ready and waiting in the anteroom. One of the operators started to get him organised into place, while the other took me to a screen in the anteroom for a look at my results. The image was all ‘black and white’, maybe better described as greyscale, but somehow some of the images were merged to give a moving picture illustrating my heart beating. One thing that was clear was that the heart is not the neat shape as seen in a pack of cards. But then that is true of spades, clubs and diamonds. An area was pointed out that had been damaged by the lack of blood, though I did not have the expertise to discern it clearly. Figures 7–9 are initial images taken at low resolution to locate the position of the heart within the body. The position relative to the shoulders and waist and from the left and right sides is not the same for everybody. Hearts are generally slightly to the left of centre but in a few people, they are to the right.

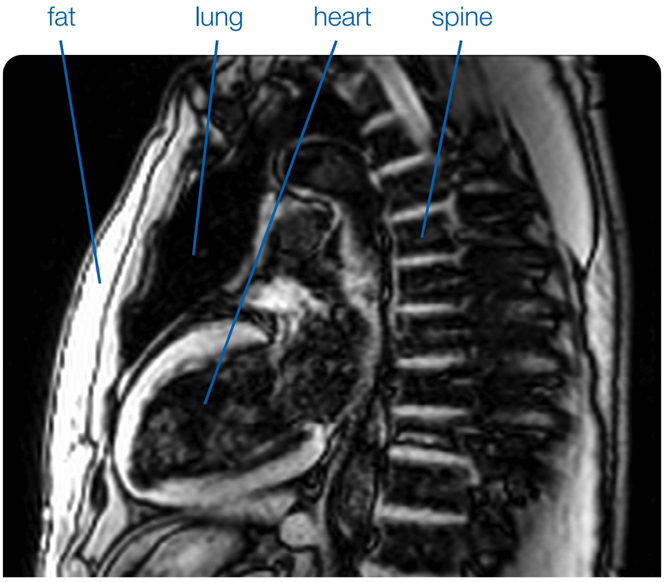

Figure 7 Side view from the left (rotated to appear upright – I was lying on my back for the scan)

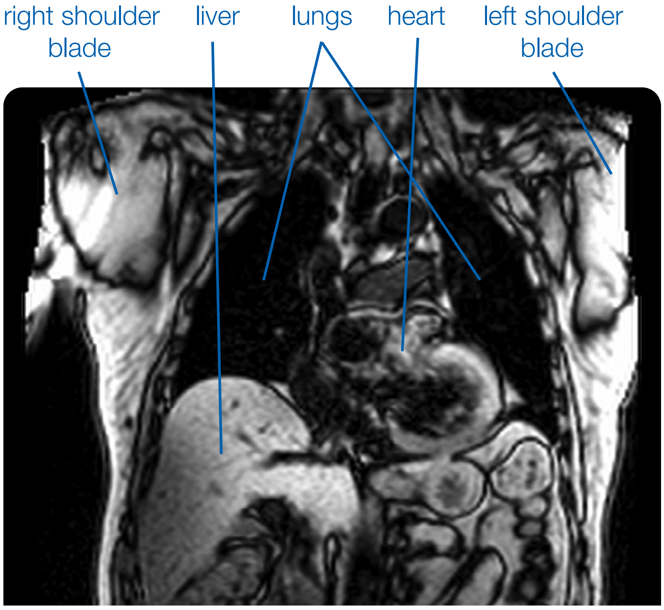

Figure 8 View from the front, taken from above while lying down; being low resolution, the heart is not as clear as in higher resolution images I was shown later

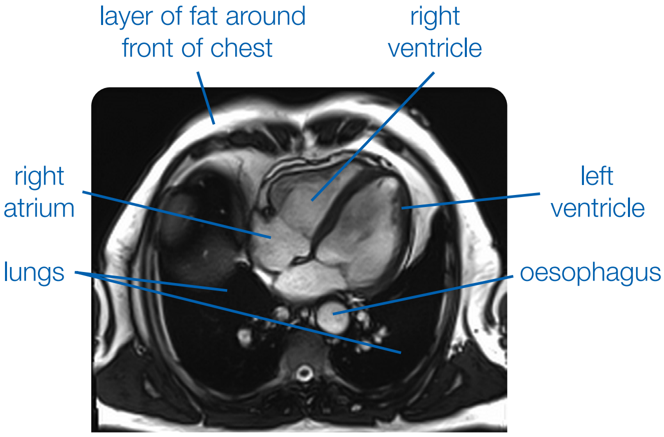

Figure 9 Cross-section view of chest region (as if viewed from the feet towards the head with the patient lying down)

Conclusion

Why have I told such a personal story? The answer is to try to be helpful to others. I have always felt quite fit, and had very little illness. In 41 years of teaching I had only 10 days' absence with 'illness', mostly with sore throats (a hazard of teaching), and continue to do the activities I choose. Afterwards, I was advised to take brisk walks but I was accustomed to doing that anyway.

I had been tempted to ignore the feeling in the chest, assuming it would go away. But being not quite like anything experienced before, it made me think that I ought to check. The medical people I saw in two hospitals over the following five days all said the same thing: if anything unusual occurs in or near the heart, get it checked as quickly as possible. You will not be wasting time.

Acknowledgments

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