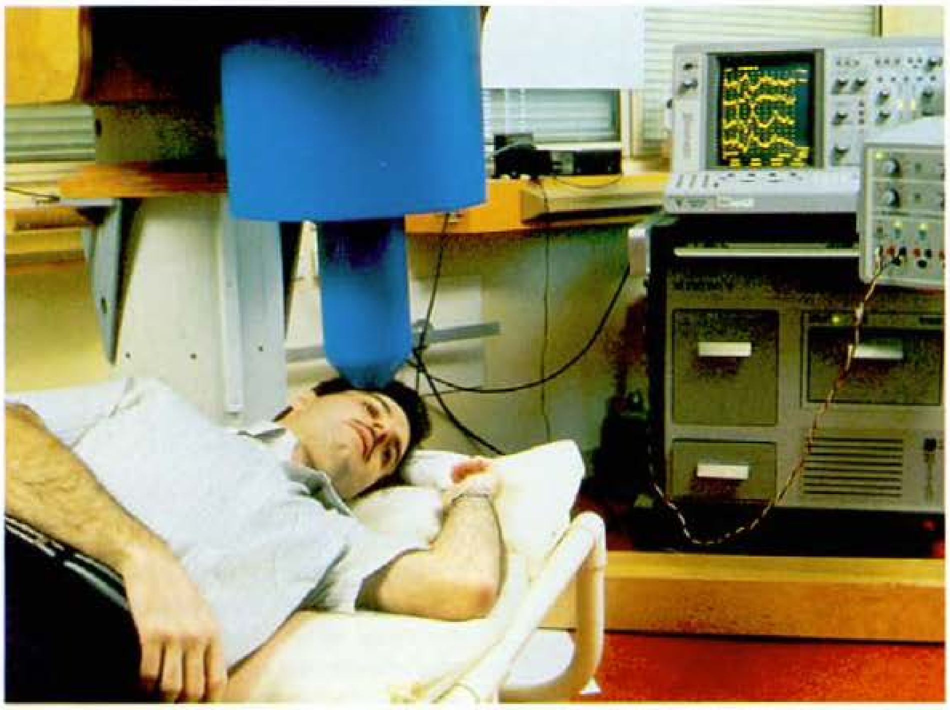
Picoteslas, SQUIDS, and 'personal magnetism'



Neuromagnetic measurements in progress at Westmead Hospital, Sydney.

We all have our own personal magnetism. By this scientists don't mean the indefinable 'charisma' that many of us may like to think we possess, but rather the physical type exhibited by bar magnets or, indeed, by Earth itself.

Although in the normal course of events objects made of iron do not rush to attach themselves to us, nevertheless we each produce tiny magnetic fields from the electricity in our bodies. In fact, most living things do this; the phenomenon is termed biomagnetism.

The tiny fields involved have always been very difficult to detect and measure, and so until recently biomagnetism has not been greatly amenable to study. But, thanks to superconductivity, that has changed in the last decade or so, and we are now upon the threshold of new developments in the study of the brain and other areas of medicine based on accurately measuring biomagnetic fields in living humans.

The story really starts in the 1780s in Bologna, Italy, where Luigi Galvani found that severed frogs' legs twitched in response to the only form of electricity available at the time — namely lightning or static discharges. This and other work led to the concept of 'galvanic fluid', or 'animal electricity'.

Although Galvani's experiments — attaching pieces of freshly killed creatures to lightning conductors in the middle of a storm — might have seemed a little outlandish to the folk in his neighbourhood, it is thanks to those studies that scientists began to appreciate the very important part that electricity plays in biology.

Perhaps the best-known example of this is the conduction of a nervous impulse in animals, but weak electrical currents also occur in most other living cells — including those of plants. Unlike the household variety with which we are familiar, biological electricity does not involve the movement of negatively charged electrons bumping from atom to atom along a wire. Rather, it consists of the diffusion within or between cells of entire ions (which are charged atoms or molecules) and hence is much slower, but, importantly, does not need metals for its conduction.

What it does require, however, is a way of separating ions of one charge from those oppositely charged so as to create a potential difference. Most biological membranes can do this to some degree by active pumping. At a later point, they then allow the accumulated ions to pass back across them by diffusion, resulting in the net movement of an electrical charge.

But where does magnetism come into all this? In 1819, the Danish physicist Hans Christian Oersted found that a current run along a wire parallel to a compass needle made the needle swing away from the wire. In other words, electricity and magnetism were somehow related phenomena. We now know that magnetised iron — such as a compass needle — is full of perpetually moving charges, which constitute electric currents on an atomic scale. (And, just like a magnet, a current-carrying coil of wire also moves in response to current in a straight wire running parallel to it.)

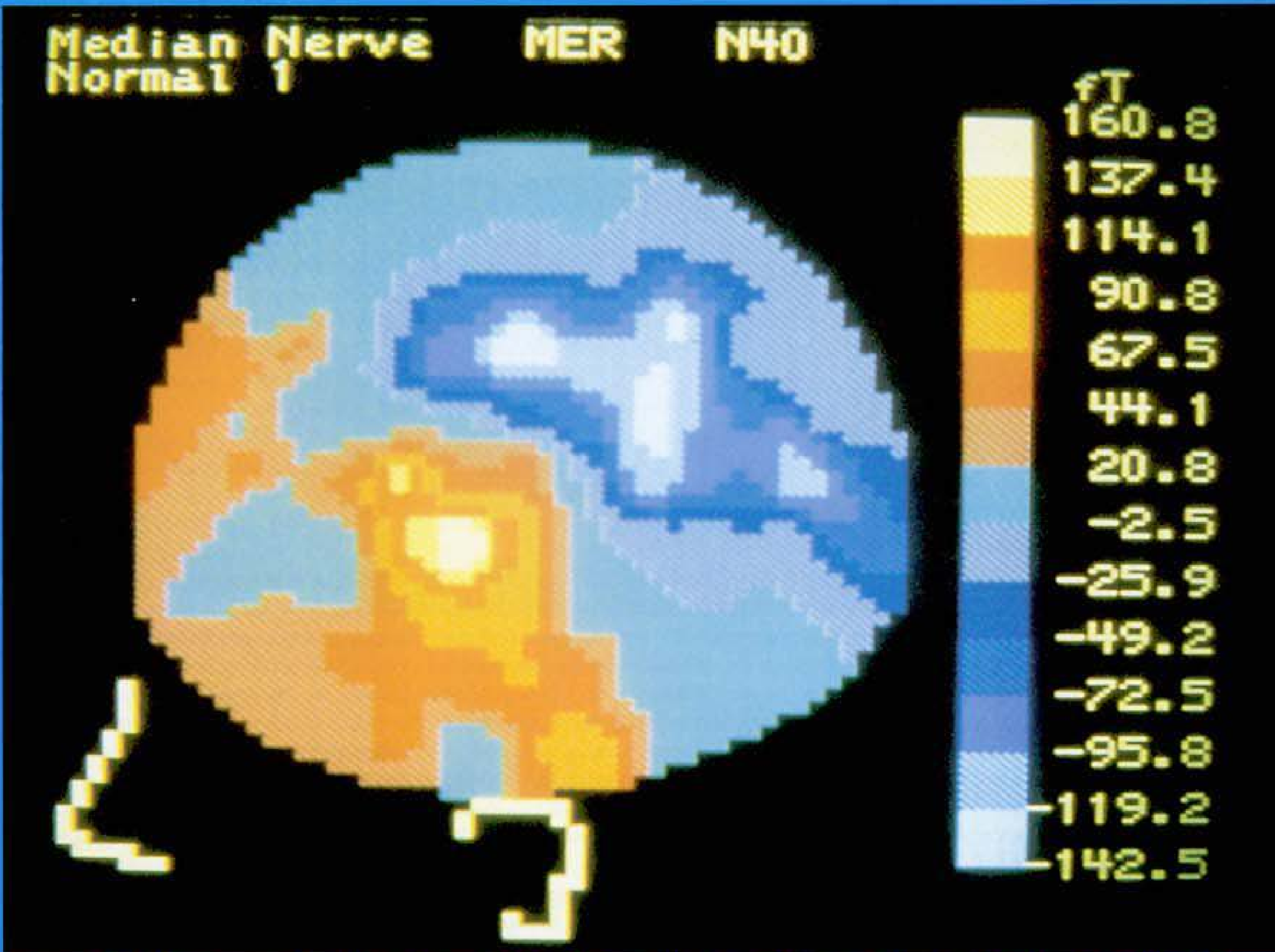
In fact, every electric current creates a magnetic field around itself, in accordance with the now well-established laws of electromagnetic induction. The ionic currents flowing in biological tissues are no exception. So the commonly measured electrical activities within the body generating, say, the electrocardiogram (ECG) and the electroencephalogram (EEG) all have their magnetic counterparts.

SQUIDS

With notable exceptions — such as the electric eel whose 'shocking' behaviour can even kill a human — most biological current flows are minute and give rise to magnetic signals so weak that they could not be detected until the development of a new class of magnetic field sensor in the 1960s. The new sensors were based on superconducting quantum interference devices (SQUIDS for short), which are the most sensitive known detectors of magnetic flux, and of current and voltage.

Being based on 'traditional' superconducting materials, like lead and niobium, SQUIDS of the original generation only operate near a temperature of absolute zero, which is achieved by keeping them in expensive liquid helium. Essentially, a SQUID is a loop of superconductor interrupted by one or more insulating barriers called Josephson junctions. The loop senses any magnetic flux passing through it, and with appropriate accessory electronics can convert this to a voltage proportional to the intensity of the flux.

The sensitivity of a SQUID is astounding; it can detect a magnetic signal of just 1 picotesla, which is 50 million



A magnetic field map measured on the surface of the head. From such a map, doctors can determine the location of electrical activity.

times weaker than the Earth's magnetic field.

We now need to digress briefly to explain the little-known units of magnetism. Magnetic flux is measured in webers; the tesla (replacing the old-fashioned term gauss) is the unit of magnetic flux density, which is closely linked to field strength, or flux per unit area. A tesla is 1 weber per sq. metre. It is approximately the magnetic field strength in most electric motors; the strength of Earth's magnetic field at the surface is about one-hundred-thousandth of a tesla. By contrast, at the surface of a neutron star, the field strength is estimated to reach about 100 million tesla.

Returning to SQUIDS, research found that Josephson junctions also have the interesting property that, when struck by microwaves, they produce a direct current voltage proportional to the microwaves' frequency. Hence, scientists can use the junctions for the business of accurately producing and measuring voltages.

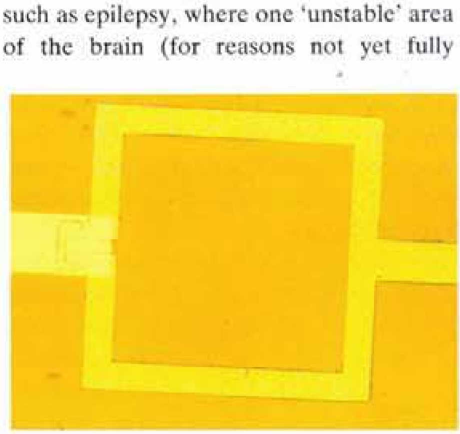
Indeed, Dr Ian Harvey and his team at the CSIRO Division of Applied Physics have been making SQUIDS for just that purpose for many years. And when doctors at the Westmead Hospital in Sydney acquired a biomagnetometer from overseas, they contacted the Division for help with its assembly, operation, and analysis of data; a group from the Division, led by Dr Graeme Sloggett, thus became involved in this collaborative project on biomagnetism.

Magnetic brains

One of the major clinical applications of the biomagnetometer is magneto-encephalography, which means simply measuring the magnetic fields within the brain. This has an advantage over the more conventional electroencephalography since it allows scientists to determine the position of the source more accurately.

Electrical measurements only detect the signals on the surface where the electrodes are; they can give little indication of the three-dimensional position of the electrical source because different tissues offer different resistance to the passage of currents, thus distorting the signals on their way to the electrodes and making it impossible to localise their source. By contrast, magnetic fields are not affected by their passage through biological material.

This magnetic transparency makes it possible to calculate — from a map of the magnetic field around a part of the body — the location and strength of the current source creating that field. The importance of this becomes apparent with a condition such as epilepsy, where one 'unstable' area of the brain (for reasons not yet fully



A thin-film SQUID made of two materials: niobium (darker) and lead-indium (appears light yellow). Josephson junctions are in the region where the two superconducting layers overlap.

established) enters a state of frantic electrical activity, which then affects the entire organ. The position of that area can influence the type of epileptic attack and its consequences, and doctors are therefore interested in locating it precisely. In a small number of cases that did not respond to conventional treatment, surgical removal of the small amount of trigger tissue, accurately located, has proved effective in controlling the seizures.

Noise

But the fly in the magnetic ointment is the problem of 'noise' — both from within the SQUID itself and from outside. In a hospital, 'magnetic noise' in the environment may be millions of times greater than the strength of the signal from the patient. It can be induced by current flow in the wiring of the building or electrical equipment, or by the movement of nearby steel objects such as lifts, cars, or trolleys.

As well, we have Earth's own all-pervasive magnetic field. Fortunately, this is constant and can be filtered out, but to minimise the other noise sources the biomagnetometer contains a set of detection coils that function as a gradiometer — that is, they detect only gradients within a magnetic field rather than the field itself. Like a gravitational field, the strength of a magnetic field drops away rapidly with the distance from the source (as the distance doubles, the field strength weakens to its square root). The gradient, which is a measure of change of strength over distance, is therefore strongest nearest the source. The gradiometer can be set to detect only strong gradients, allowing the biomagnetometer to discriminate against distant magnetic sources, even though these have a stronger field strength than the subject has.

Like any other electronic device, a SQUID generates its own noise. The noise energy is very small, mainly because the operating temperature is so low, but it's still significant in terms of the tiny signals occurring in biomagnetic measurements. To solve this problem the scientists use repetition. They give a stimulus to evoke a particular electrical (and hence magnetic) response in the brain — for example, they may sound a tone or flash a light — and repeat it 100 or 1000 times. The response to the stimulus — the signal — is the same every time and when all the responses are added together the signal stands out clearly from the random background noise. This trick could also be used to eliminate magnetic noise from regions of the body other than those being measured.

Of course, taking many such readings is time-consuming. It takes from a few minutes to about half an hour to get a clear reading from just one point. In order to produce a useful 'map' of the magnetic activity of the whole brain, scientists would need a minimum of about 50 such points and, at half an hour each, that involves asking somebody to give a great deal of time! Dr Sloggett's research involves finding ways of improving biomagnetometers to make them a little more practical for everyday clinical use. He is working in conjunction with Dr Evian Gordon and his team from the Neuroscience Unit of the University of Sydney and Westmead Hospital.

An obvious first improvement is for the machine to have more than one channel. Dr Sloggett believes it's possible, by using many SQUIDS and the necessary accessory electronics, to make a machine with the ability to measure 80 points simultaneously and so give a quick magnetic picture of an entire organ. Measuring the activity of so many points throughout the brain simultaneously has never been done, and it would be a major advance because — with the activity of the brain constantly changing — the measurement of points sequentially is much less useful.

Secondly, it's possible to increase the sensitivity — that is, reduce the intrinsic noise — of the SQUIDS. A DC (direct current) SQUID is much more sensitive than the RF (radio frequency) ones currently in use in biomagnetometers.

Even better news is that physicists now know how to make DC SQUIDS in a thin-film form, by methods similar to those used in the microelectronics industry. This way of producing them would make them cheaper than the RF version, and so acquiring many of the former for a multichannel machine need not be prohibitively expensive.

The ability to watch a large area of the brain in action may help researchers unravel a little of the greatest remaining mystery of human biology: the functioning of the 'higher' brain areas that are responsible for thought, decision-making, and personality.

Recent advances in the field of superconductivity have led to the development of so-called 'warm' superconductors that can allow the passage of a current with minimal resistance at temperatures as high as −196°C. Although not exactly room temperature, such a chill can be acquired by immersion in liquid nitrogen, rather than the far more expensive liquid helium (boiling point −269°C) that the older generation of materials needed (see *Ecos* 59). Scientists at the Division of Applied Physics have already demonstrated DC and RF SQUIDS that are effective at the temperature of liquid nitrogen, but the devices are far from being ready for practical use yet.

It's worth while for a hospital to possess a quick and 'user-friendly' biomagnetometer; although of greatest use in neurology, it need not be confined to studying the electrical activity of the brain. In cardiology, it could detect the activity of the heart, especially the conduction of the electrical impulse through its tissues. Various conditions, such as the death of a portion of heart muscle, can affect this, leading to uncoordinated contraction. Biomagnetic measurements could distinguish between living and dead portions of the heart muscle, and locate them accurately.

Uses in other areas of medicine could include detecting the deposition of iron (which in certain conditions can accumulate in the liver with pathological results) and helping in the detection of particles of certain metals that, breathed in and accumulated in the lungs, can cause tissue destruction.

The real 'beauty' of the biomagnetometer over current medical techniques is that, although it has the ability to both detect the brain's functioning and provide a good image, it is, to use the jargon, 'non-invasive'. At the moment, measuring brain activity (and hence its operation) usually involves the injection of radioisotopes. Imaging techniques such as the CATscan subject patients to X-rays (albeit in relatively small doses), and nuclear magnetic resonance involves exposing them to very large magnetic fields — although, as far as we know at the moment, this presents no danger. By contrast, a biomagnetometer does not 'send anything in' — it does nothing but detect what the body is broadcasting.

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More about the topic

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