Magnetic fields of the human body

Inside the MIT shielded room, the magnetic field of a subject's heart is measured by a superconducting magnetometer. Shielding is provided by the room's five-layered walls (three of moly permalloy and two of pure aluminum) and by negative-feedback loops. Although nanogauss fields can be detected, a normal heart produces magnetic fields in the microgauss range, as figure 3 indicates. Figure 1

Developments in ways to measure the extremely weak magnetic fields emanating from organs such as the heart, brain and lungs are leading to important new methods for diagnosing abnormal conditions.

David Cohen

In France, around 1780, many Parisians believed in curing their illnesses by magnetism. To perform this cure, they sat in a group around a tub containing "mesmerized" water and iron filings; this was part of the cult introduced to Paris by Dr Franz Mesmer. He proclaimed that animal magnetism of the human body controlled the flow of a universal fluid through the body and that illness resulted when there was an obstacle to that flow. The illness would be cured by magnetically redirecting the fluid with arrangements such as the filings and water.

Today, two hundred years later, we know that the human body is indeed magnetic in the sense that the body is a source of magnetic fields, but this body magnetism is very different from that imagined by Mesmer. Furthermore, today's body magnetism may also be medically useful—but the apparatus involved is considerably different from water and iron filings in a tub! This modern apparatus is not used in guiding a fluid through the body but in measuring the magnetic fields produced by the human body. A growing number of physicists, engineers and medical specialists are involved in these measurements and their interpretation.

This article deals with a new area of research, in which magnetic fields from the human body are measured that are as weak as 1×10^{-9} gauss—about one-billionth of the Earth's magnetic field. Although detectors consisting of large coils were useful in the early measurement of the stronger fields from the heart, it was the development of both the superconducting detector and new shielding techniques that were the stimulus for most of the measurements of the body's magnetic fields. The superconducting detector allows great sensitivity and the shielding reduces or excludes the magnetic background. The body's fields have now been measured in at least ten laboratories, and are the subject of eight doctoral theses and about fifty published papers. These are not especially large numbers, but the activity in this area is growing as more physicists look for medical applications of their know-how in superconductivity and magnetism. Figure 1 shows a heart measurement being made in the shielded room of our laboratory.

This article is not concerned with the biological effects of an external field applied to the body, an area of research in which my colleagues and I are not involved.

Mechanisms of field production

How are magnetic fields produced by the body? There are two different mechanisms.[1] The first is field production by naturally occurring electric currents in the body. These are currents of sodium, potassium and chlorine ions that muscles and nerves (often called "excitable tissue") generate in the process of contraction or signal transmission. The currents flow through the general mass of fluids and tissues of the body, called the "volume conductor." They can be fluctuating (ac) and produce a fluctuating magnetic field, or they can be steady (dc) and produce a steady magnetic field. This mechanism is illustrated in the first part of figure 2, in which the generator of current in the tissue is represented in the simplest way, by a current dipole, as a basis for discussion further on. (The current dipole is the current analogue of the charge dipole, and is distinct from the magnetic dipole which is a small current loop). The heart and the brain are well known as organs that generate ion currents. The current from the heart muscle, when measured with electrodes on the skin, produces the electrocardiogram (ECG); the same current produces a magnetic field around the torso which, when measured, is called a magnetocardiogram (MCG). The current from the brain produces the electroencephalogram (EEG) at the scalp; it also produces a magnetic field around the head which, when measured, is called a magnetoencephalogram (MEG). Because blood is electrically neutral, blood flow constitutes zero electrical current and produces no magnetic field.

The second way in which magnetic fields are produced is by magnetic material in the body. In general, magnetic material produces a field in reaction to an external field applied to the material; this material can be diamagnetic, paramagnetic or ferromagnetic. Although the body certainly contains dia- and paramagnetic substances, we will confine ourselves here to ferromagnetic material; in particular, we will deal with the remanent field of ferromagnetic particles, produced after the applied field has been removed. These particles do not occur naturally in the body, but are contaminants. By far the most common type of particle involved here is magnetite (Fe_3O_4), which is both insoluble in the body and harmless. These particles can be found in several organs of the body but, as we shall see below, their presence in the lung is of the most interest at this time.

The strengths or levels of magnetic fields produced by either of these two mechanisms is shown in figure 3. A distinction is made between fluctuating and steady fields because the background and the method of measurement is different in the two cases. Fluctuating magnetic fields are produced by all the organs in the body that consist of or contain muscle or nerve. In contrast to other muscles in the body, the fibers of the heart muscle depolarize or "fire" synchronously; because of this the heart produces the strongest fluctuating magnetic field, at a peak somewhat greater than 1×10^{-6} gauss in normal subjects. Some abnormal hearts produce larger fields. Skeletal muscles, which can be massive but depolarize asynchronously, produce a weaker magnetic field: Some of the large muscles, when flexed, produce high-frequency peaks of about 1×10^{-7} gauss. The strongest magnetic field from nerve tissue is from the brain. The normal brain yields its largest fields during sleep, about 3×10^{-8} gauss in amplitude; epilepsy can produce much larger fields. In comparison to the weak fields from muscles and nerves, the fluctuating component of the magnetic background can be very strong: several milligauss in an urban environment, due to rotating machinery, 60-Hz current and moving vehicles. Therefore measurement of the body's fluctuating fields in an urban environment involves measurement of weak fields in a background that can be three or four orders of magnitude greater. The fluctuating background in a rural environment is usually considerably less, although still much greater than the body's ac fields.

Steady magnetic fields are produced both by magnetite particles in the lungs and by steady currents from some or-

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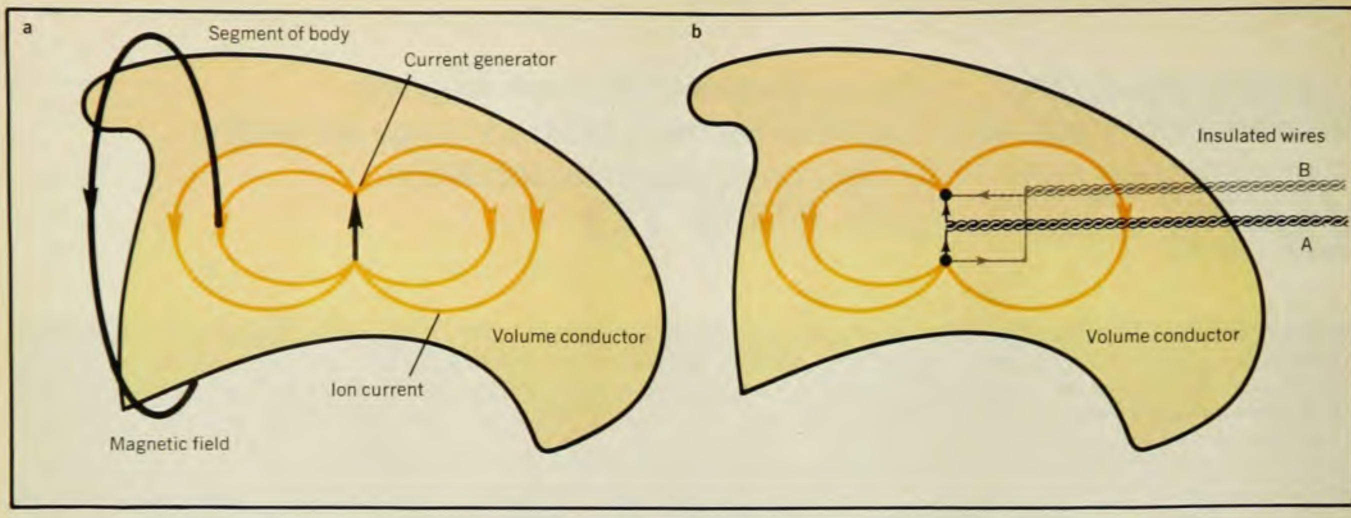


One way the body produces magnetic fields is by currents from muscles and nerves. Such a source, shown in **a** as a current dipole, generates ion currents, which in turn give rise to a magnetic field. In part **b**, such a source is simulated by one of two pairs of wires, A or B. The magnetic field can reveal which of these pairs is used; potential measurements taken at the surface can not. Figure 2

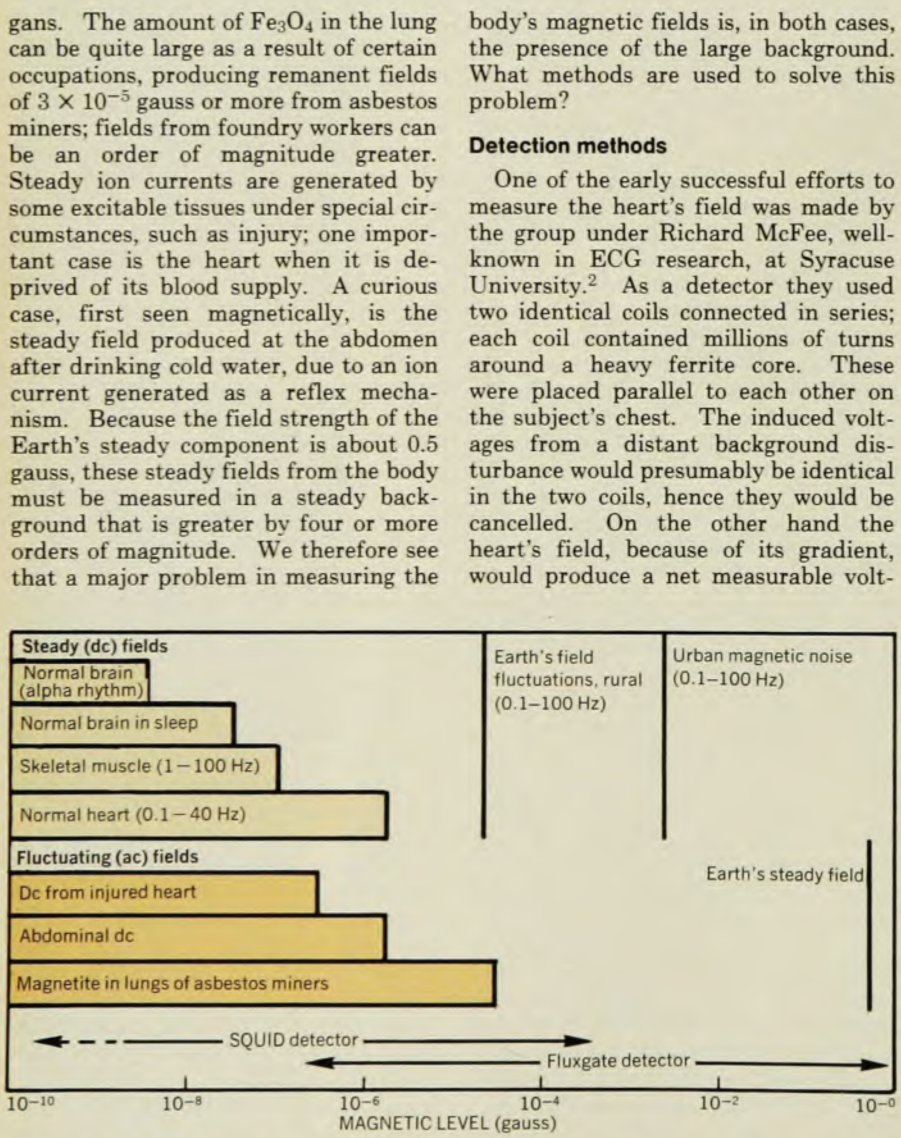
gans. The amount of Fe_3O_4 in the lung can be quite large as a result of certain occupations, producing remanent fields of 3×10^{-5} gauss or more from asbestos miners; fields from foundry workers can be an order of magnitude greater. Steady ion currents are generated by some excitable tissues under special circumstances, such as injury; one important case is the heart when it is deprived of its blood supply. A curious case, first seen magnetically, is the steady field produced at the abdomen after drinking cold water, due to an ion current generated as a reflex mechanism. Because the field strength of the Earth's steady component is about 0.5 gauss, these steady fields from the body must be measured in a steady background that is greater by four or more orders of magnitude. We therefore see that a major problem in measuring the body's magnetic fields is, in both cases, the presence of the large background. What methods are used to solve this problem?

Detection methods

One of the early successful efforts to measure the heart's field was made by the group under Richard McFee, well-known in ECG research, at Syracuse University.[2] As a detector they used two identical coils connected in series; each coil contained millions of turns around a heavy ferrite core. These were placed parallel to each other on the subject's chest. The induced voltages from a distant background disturbance would presumably be identical in the two coils, hence they would be cancelled. On the other hand the heart's field, because of its gradient, would produce a net measurable voltage. Magnetocardiogram recordings were made that indeed showed the heart's peak field above the background, especially in a rural setting. However, the two problems of exactly balancing two large coils against urban background and of the inherent coil noise worked against the acceptance of this system.

I had used a somewhat different approach in dealing with the magnetic background, perhaps because of my years around high-energy accelerators where shielding is routinely used against a large radiation background. My approach was to construct a magnetically shielded room, with the support of my colleague Lester Winsberg. After a technique was found[3] to increase the permeability of the two shielding layers, this room was effective in reducing the background, often below detectability. The detector was a single coil, which measured one component of the field instead of the gradient. With this system the heart's signal was readily seen—and proven[4] to be the heart's actual magnetic field. This field was then mapped in some detail, and the existence of fields from other organs was also demonstrated.

Later, at MIT's Francis Bitter National Magnet Laboratory, my associates and I constructed an elaborate shielded room that reduced the background much further.[3,5] This room is shown in figure 1. Its shielding is accomplished by three methods: by ferromagnetism, by eddy currents and by an active system in which an external detector feeds a negative-feedback loop. The room was designed to reduce most of the external background below the small magnetic noise expected from the inner ferromagnetic layer due to magnetostrictive and spontaneous domain phenomena. Specific features for measuring the body's fields incorporated

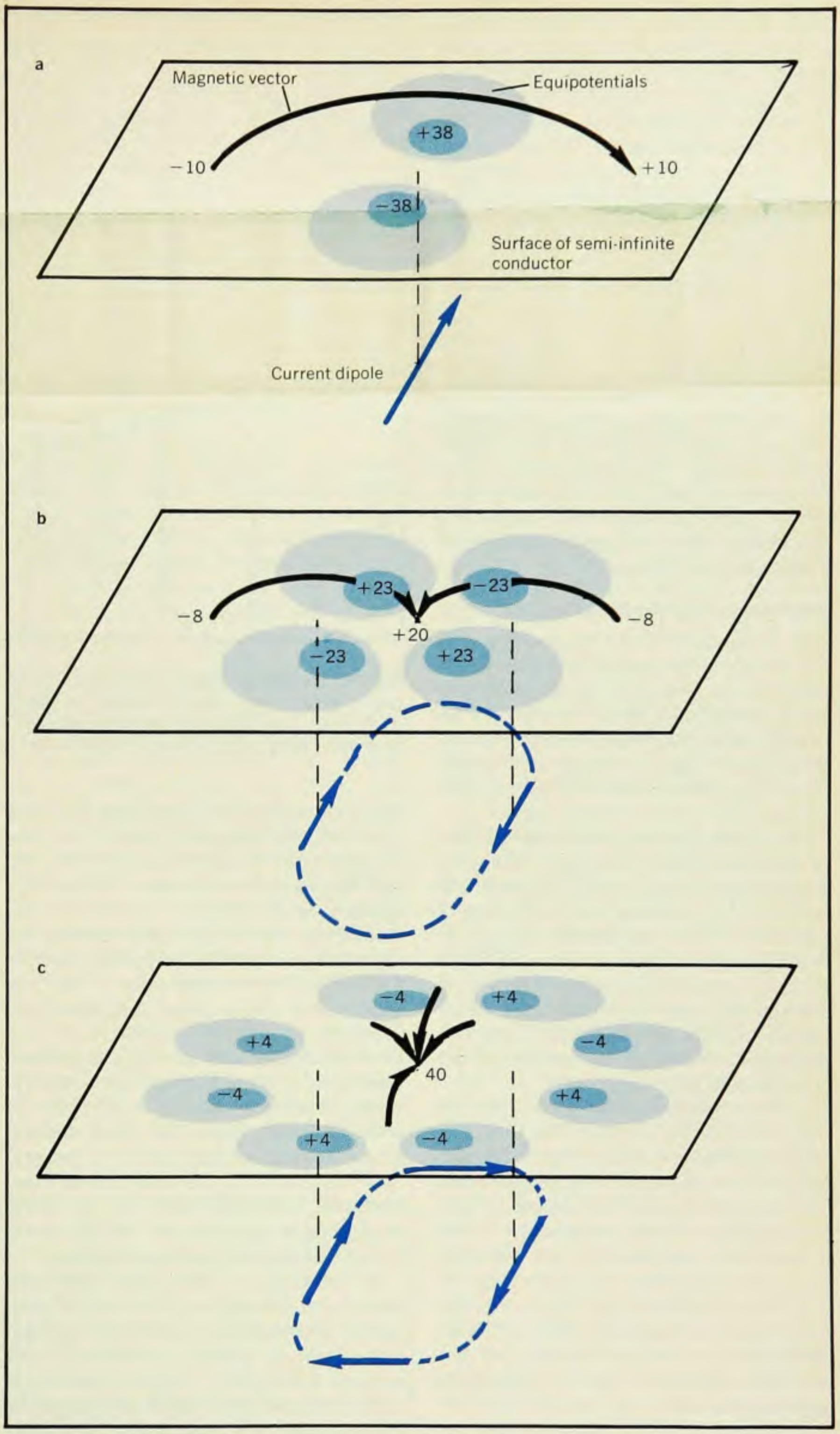


Levels of the fields around the body and in the background. The strongest fluctuating field is over the lower part of the heart; the strongest steady fields, in welders and asbestos miners, are produced by particles of iron oxide in the lungs. The bottom of the diagram indicates the sensitivity of the two detectors, fluxgate and SQUID, for a 1-Hz bandwidth; the broken line shows that the limit moves to the right with greater bandwidth. Figure 3 into the design of the room included an independent suspension of the floor, which prevents body movements from coupling to the inner shielding layer and thereby producing magnetic signals.

Fortuitously, when the room was built, a detector that was beautifully suited to the shielded room for measuring the body's fields had just become available. This detector, a version of the Josephson junction known as the SQUID (superconducting quantum interference device), was developed by James Zimmerman.[6] Compared with the coil detectors used before, the sensitivity of the SQUID is greater by several orders of magnitude and, unlike coils, the SQUID responds in frequency down to dc. It can be used as a simple one-component magnetometer, as we have usually done, or as a gradiometer. Now, five years after we first used it, the hassles inherent in any new superconducting device are largely gone and the SQUID is operated as a routine instrument; the superinsulated dewar is refilled with liquid helium only every five days or so, and the system runs for months without maintenance.

The rms value of the internal detector noise, which defines the limit of sensitivity, increases as the square root of the bandwidth used and so is expressed in gauss $Hz^{-1/2}$. Its present value, 1.6×10^{-10} gauss $Hz^{-1/2}$, is low enough to allow measurement of all the body's fields except the weaker events from the brain. By the end of the year, however, we expect to have in operation a new SQUID system specifically designed for brain measurements, with internal noise down 50%.

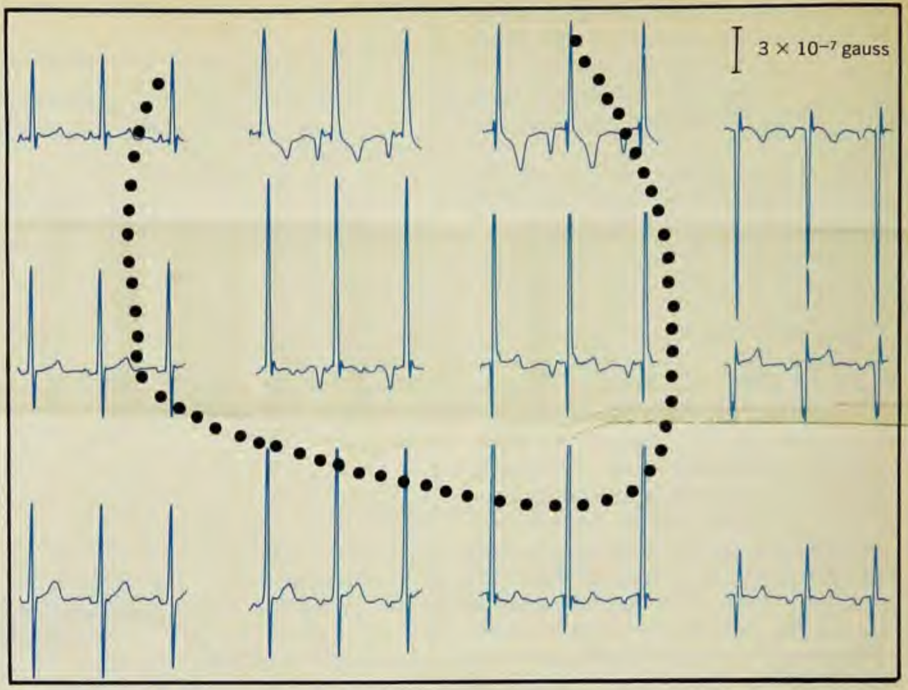
The urban and laboratory background that is present during the regular workday is sufficiently reduced by the room to allow most body measurements to be made with the SQUID during these hours. However, measurements of the brain are best made during the evening or weekends when the background in the room is below the internal noise of the detector. When the new SQUID is brought into operation, we expect that noise from the inner shielding layer, now largely unseen, will become a problem or a limitation. Incidentally, the strong Bitter magnets in our laboratory building do not present much of a problem because they are mostly powered by dc, and so only steady fringing fields, which are only small increments to the Earth's steady field, reach the vicinity of the shielded room. In fact, the presence of both strong magnets and low-field facility in the same building allows us to tell our visitors that we span a magnetic range of fifteen orders of magnitude!



Surface-potential versus magnetic-field measurements for a semi-infinite volume conductor. The numbers shown are normal components of magnetic field and calculated potentials due to one, two and four dipoles. As the number of dipoles is increased around a loop (broken lines) the magnetic field becomes more pronounced while the potentials decrease, and are swamped, in a realistic situation, by the ever-present noise. Figure 4

Although the more accurate measurements of the body's fields have been made in the MIT shielded room with the SQUID one-component magnetometer, gradiometers have recently been used and show promise for some of these measurements; the advantage of gradiometers is that they can be used with little or no shielding. These consist of two or more magnetometers that are oriented so as largely to cancel the background, as did the Syracuse coils, but without the coil's disadvantages.

Two types of gradiometers have been used: the fluxgate and the SQUID. The fluxgate is operated at room temperature and is inexpensive; we have found it to be ideal for detecting steady fields due to Fe_3O_4 in the lungs at levels greater than 5×10^{-7} gauss, as indicated in figure 3. The SQUID gradiometer usually consists of two opposing detection elements about 7.5 cm apart; they are very well balanced, with somewhat less sensitivity than the SQUID magnetometer. This type of system has been used by physicists at a number of laboratories. Toivo Katila and his collaborators in Finland have been mapping abnormal heart fields without shielding in a rural location; they are now constructing a shielded room. Zimmerman and his collaborators in Boulder have been detecting the brain's field in a chamber shielded with aluminum. Samuel Williamson and Doug Brenner at New York University have shown great persistence in measuring the brain's field, without shielding, in downtown Manhattan!



Partial magnetocardiogram map of a normal person, with an x-ray projection of the heart superimposed. The map is produced by taking MCG's (as in figure 1) at junctions of a 5-cm by 5-cm grid. The MCG has the same features as the ECG, but with different relative magnitudes. New information is beginning to be extracted from such maps. Figure 5

Why measure these fields?

It is clear that the measurement of the body's weak magnetic fields in the presence of magnetic background presents problems. Why then go to the trouble of making these measurements? What advantages do magnetic measurements have over other methods of measuring events in the human body?

The first advantage is the capability of detecting some generators in the excitable tissue of the body that cannot be detected by potential measurements on the skin. These generators can be divided into two types: those having a particular spatial distribution in the tissue and those having a particular distribution in time, in particular those producing dc. We will first discuss the distributions in space.

Let us consider three ideal cases. In the first case we compare the magnetic field with the potential, both at the surface of a semi-infinite volume conductor, as we increase the number of current dipoles in the conductor. As in figure 4, we increase the number from one to two to four; with each step the potential decreases over the entire surface while the magnetic field increases at one area. Let us continue the process and allow the number of dipoles to approach infinity. As a result, the surface potential will decrease to zero everywhere, but there will continue to be a magnetic field. Therefore potential measurements cannot show the presence of the loop, but a magnetic measurement will reveal the loop's presence and some of its parameters.

As an aside, we should note that there are opposite examples in which there is a surface potential but no field, such as a radial-current dipole in a spherical conductor. In our second case, shown in figure 2b, current is generated by two electrodes in a conductor, such as a saline solution. We feed these electrodes by either pair A or pair B of twisted, insulated wires. Let the current be dc in order to avoid radiation and displacement current. Surface potential measurements cannot reveal which pair feeds the wires because the insulator, assumed to be perfect, shields the wires electrostatically. On the other hand, the external magnetic field is produced both by current in the volume conductor and in the non-twisted elements of wire; a magnetic measurement therefore reveals which pair of wires is used. These two cases demonstrate spatial arrangements of generators that can only be determined magnetically, although only in an ideal world which contains an infinite number of dipoles or a perfect insulator.

In contrast, a third case has been used in an attempt to show that all generator information available in the magnetic field is already available in the surface potentials. Let the wavefront of depolarization in the heart muscle be represented, as is customary, by a moving layer of current generator about 1 mm thick. In the biophysics literature this is described by the vector field $\mathbf{J}_i$, called the "impressed current density," which is nonconservative and similar to the chemical ion current in a battery. The current in the volume conductor and the surface potentials are functions of div $\mathbf{J}_i$, which equals the charge density at the surfaces of the layer. It has further been shown that the external magnetic field is a function both of div $\mathbf{J}_i$, the contribution from the volume-conductor current, and of curl $\mathbf{J}_i$, the contribution from the layer.

Generally a determination of div $\mathbf{J}_i$, still leaves curl $\mathbf{J}_i$ undetermined. Up to this point it therefore appears that only the magnetic field can yield the new information contained in curl $\mathbf{J}_i$; this is similar to information that distinguishes pair A from pair B in figure 2b. However, an idealization stating that $\mathbf{J}_i$ can only be a uniform field is now added; some feel that this is a good representation of electrophysiological reality. The results of this restriction are that curl $\mathbf{J}_i$ is determined by div $\mathbf{J}_i$, and that therefore there is no new information in the external magnetic field: In figure 2b this is equivalent to allowing only wire pair A, so there is no question for magnetic measurements to answer.

What about noise?

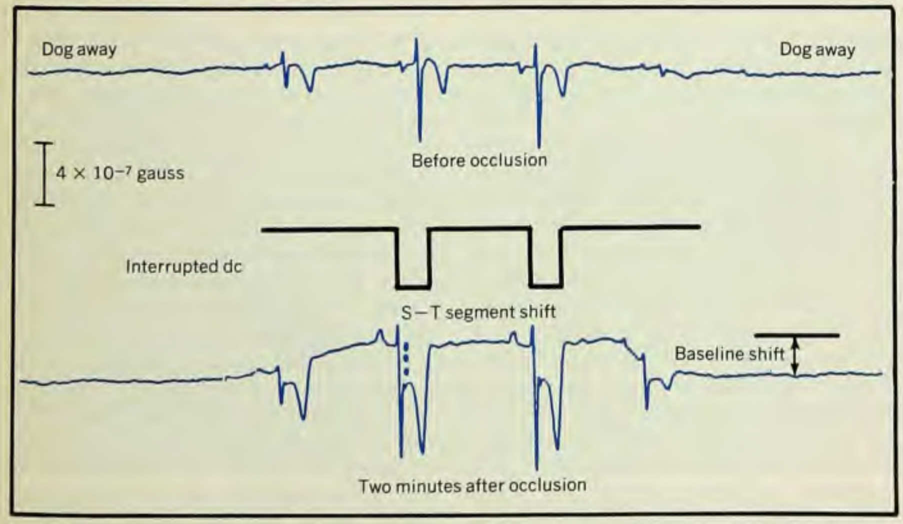
What happens if we now move into the real world? For our purposes, the most important new fact is the presence of noise. As used here, noise consists of the errors, when solving backward from measured potentials to find the internal generators, due to uncertainty in dimensions and conductivities of the inhomogeneous internal tissue and in electrode placement. This noise can always be referred to a surface-potential equivalent. We now ask the question: "What generator configurations can not be determined from potential measurements because of noise but can be determined from magnetic measurements?" In our first case (figure 4) we must drop the idealization of an infinite number of dipoles—but the case is again valid if we have enough dipoles around the loop to reduce the surface potential below the noise. This may happen with as few as four dipoles, in view of the tenfold decrease of potential seen with this configuration. Magnetic measurements, then, can reveal generator arrangements of this type. In our second case (figure 2b) the insulator on the wire can no longer be perfect; but the surface potential resulting from leakage need only be lower than steady noise so that, again, pair A can not be distinguished from pair B by potential measurements. Avoiding for the moment the previous controversy of curl $\mathbf{J}_i$ and pair B, this case suggests that magnetic data can reveal generator arrangements in the following broad category: a poor conductor that encloses some generators and thereby reduces their surface potentials below the noise. This might apply, for example, to the skull, which is a poor conductor and known to degrade the EEG potentials.

Whereas the first two cases could be modified for the real world, the third case loses its validity in two ways. First, consider its conclusion that there is no new information in the magnetic field; this is equivalent to stating that zero surface potential means zero magnetic field. However, the zero-potential concept is not meaningful in the real world with noise. This case could again be valid if it showed that configurations giving surface potentials below the equivalent noise always give magnetic fields below the magnetic noise; our first case proves that it cannot do this. Second, new experimental evidence cited by Robert Plonsey[8] contradicts the concept of a uniform $\mathbf{J}_i$ when used for magnetic determinations. This idealization of $\mathbf{J}_i$ will continue to be valid for potential measurements far from the layer because they are sensitive only to the charge at the layer surfaces and not to twisting or bending of the source current within the layer; however, magnetic measurements, via curl $\mathbf{J}_i$, *are* sensitive to these internal details. The recent evidence favors a complicated zig-zag structure of the source current, so that a uniform $\mathbf{J}_i$ is an improper idealization when considering magnetic fields. In terms of figure 2b, this evidence suggests that the generators are internally much more complicated and "twisty" than wire pair A. Future magnetic measurements may well reveal generator distributions that are spiral or circulating source currents within the layer.

The time distributions of current generators that are of interest magnetically are the very high and the very low frequencies. What happens magnetically at the higher frequencies due to reactance is not yet clear, and we here discuss only the low-frequency end. The important source of dc is injured muscle and nerve tissue, which generates a steady current called the "current-of-injury." The external detection of this injury current would be clinically important, especially for the injured heart. Unfortunately, most steady currents from internal organs can not be measured with skin electrodes; this is due to large contact potentials with the skin that mask the smaller internal voltages to be measured. Magnetic measurements, on the other hand, do not involve skin contacts and are a direct probe of deeply situated steady currents.

The second advantage of magnetic measurements of the human body involves ferromagnetic particles, especially of Fe_3O_4. These particles can exist in the lungs, and only magnetic measurements around the chest can determine the quantity, distribution and other parameters of these particles. As we will see, the measurement of these particles in the lungs can yield some important research and diagnostic information.

We will now present some representative measurements of the body's fields. Although a large amount of data from various locations around the body has been accumulated, we will confine the data to three organs: the heart, the brain and the lungs. The measurements shown here were made with the SQUID in the MIT shielded room.



The dc magnetocardiogram of an anesthetized dog before and after coronary occlusion, in which the blood supply of the heart is experimentally blocked, shows that a pathological feature of the ECG called the "S–T shift" is due to an interrupted steady current. This finding is the first clear application of magnetic detection techniques to medical diagnosis. Figure 6

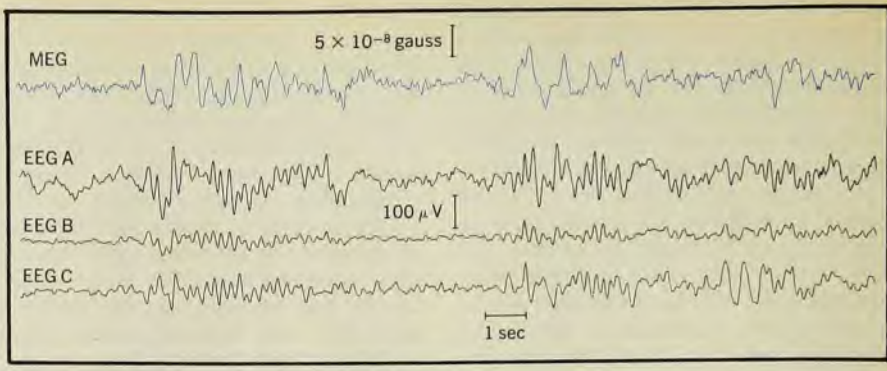
Magnetic field of the heart

The heart has been the subject of more magnetic-field studies than any other part or organ of the body. This is because of these facts: The heart signals are relatively large and therefore more easily measured with accuracy, and a great deal is already known about the electrical activity of the heart from the ECG and more elaborate surface potential measurements. Hence the MCG is amenable to preliminary analysis. Furthermore, the heart presents an important medical problem—new, effective diagnostic techniques could save many lives.

Magnetic measurements of the heart are divided into two groups, based on bandwidth: The frequency range from 0.1 Hz to 40 Hz yields the ac MCG, while that from dc to 40 Hz yields the dc MCG. Let us first review studies of the ac MCG.

The ac MCG is produced by the same class of current as the ECG, which is also an ac recording, and therefore contains the same well known features or deflections as the ECG. These include: the QRS complex, which is the largest deflection and is due to the wave of depolarization sweeping through the ventricles; the T wave, which follows QRS but is smaller and broader, and is due to the repolarization of the ventricles; the P wave, which is smaller yet and narrower, just precedes QRS and is due to depolarization of the atria. Because the way the MCG samples the fluctuating currents is very different from that of the ECG, the ratios of these features to each other are different in the two methods, and the ratios vary with location around the torso. An ac MCG map of a normal man, in the standard format used in our laboratory, is shown in figure 5. Similar maps from a large number of normal[9] and abnormal heart subjects have been recorded as part of a program to evaluate the new fundamental or diagnostic information in the MCG that is not available in the ECG.

We have taken two approaches in analyzing these MCG's. The first approach, in collaboration with Eugene Lepeschkin of ECG renown, has been



Simultaneous magneto- and electroencephalograms from an epileptic subject exhibit both similarities and differences. The MEG is the component normal to the right temple, while the EEG's are taken at the right temple, above the right ear and at the back of the head. The large slow delta waves (induced by hyperventilation) are present in both types of recording but the 5-Hz theta waves present in the EEG's are largely absent in the MEG. Figure 7

simply to compare each abnormal MCG map with the subject's ECG as well as with normal MCG maps. The idea was to look for visual differences, which would then be a clue for embarking on a more detailed analysis. Lepeschkin found that the MCG yields information not seen on the ECG with a number of abnormalities; therefore for these specific abnormalities, the MCG is potentially of particular value and will be pursued further. However, these MCG maps have not been compared with the full potential maps of these subjects, of which the ECG is only a part; this would have been the most meaningful visual comparison.

The second approach has been to work backward from the measured MCG's and to solve models of the current-dipole generators in the heart; as with surface potentials, nature does not allow a unique solution, and so various models must be used. Some theoretical groundwork had already been laid by David Geselowitz and his group[10] at Penn State University. In our laboratory, Hidehiro Hosaka of the Nihon Kohden Kogyo Company of Tokyo digitized many MCG maps and performed computer calculations based on the following considerations:

In certain conductor geometries the external magnetic field produced by an internal current dipole is a function of the dipole itself and receives no contribution from the currents generated in the volume conductor by this dipole. This interesting fact is readily proven for the magnetic field produced by a current dipole in an infinite homogeneous conductor and for the normal component of external field produced by a dipole in a semi-infinite conductor. The calculations of Hosaka and Neil Cuffin at our laboratory and Milan Horacek of Dalhousie University show that this fact is also approximately true for the heart generators in the human torso. That is, the magnetic-field component normal to the chest produced by the heart is largely due to equivalent-current dipole generators within the heart; the totality of the current that the heart produces within the torso can be largely ignored. The result is a great simplification in solving backward from the external magnetic fields to find the equivalent current dipoles within the heart; the number of steps used in solving for the equivalent current dipoles from the normal component of external field is now identical to that in which the equivalent charge dipoles is found from the surface potentials. At present, solutions from the magnetic field have been obtained for several cases, normal and abnormal, and these are being studied for new generator arrangements. As expected, the solutions reveal at least the same gross features of the heart's electrical activity as determined from the ECG; some of the dipole arrangements do appear to reveal additional information. However, this work is only beginning.

In animal experiments, the dc MCG was used for an investigation of hearts that were injured by curtailment of their blood supply, thereby generating a steady injury current. Ischemia is the associated condition in which the blood supply to the heart has been diminished; this can lead to angina or infarction (heart attack). Although this steady current is not directly detectable with surface potential measurements, scientists have conjectured for many years, but not adequately proven, that it can be indirectly detected on the ECG in the following way:

This current must be interrupted for a short period in each heart cycle, during depolarization, when the heart muscle is largely isopotential. The dc, therefore, is in fact an interrupted dc and therefore has an ac component, which makes it detectable on the ECG. This ac component or event, called the S–T segment shift and shown in figure 6, is important in the diagnosis of angina and infarction. The source of this component has never been clearly proven because of the difficulty of measuring steady voltages on living surfaces.

Larry Kaufman and I undertook[11] to make simultaneous magnetic measurements of the injury current and the S–T shift and verify their relationship. As is customary in heart experiments we used anesthetized dogs; these had been surgically prepared so that the coronary artery could be occluded by external manipulation, thereby inducing ischemia or infarction in the heart in a controlled way. The dc MCG of each animal was recorded in the shielded room before and during occlusion. A typical result is shown in figure 6.

The dc MCG was recorded in the following way: Starting with the animal out of SQUID range, it was then moved up to the SQUID for a few seconds and later moved away again. The baseline shift of the output is then a measure of the steady field, and this in–out technique is the standard way in which we measured a weak steady field in a much larger steady background. The steady background in the shielded room for these measurements was about 3×10^{-5} gauss, although this technique can cope with a larger steady background. The study of a number of animals occluded in this way showed[11] that the same S–T segment shift as seen on the ECG is actually due to the periodic interruption of the primary injury current. This result is the first clear application of magnetic detection to electrophysiology and medical diagnosis.

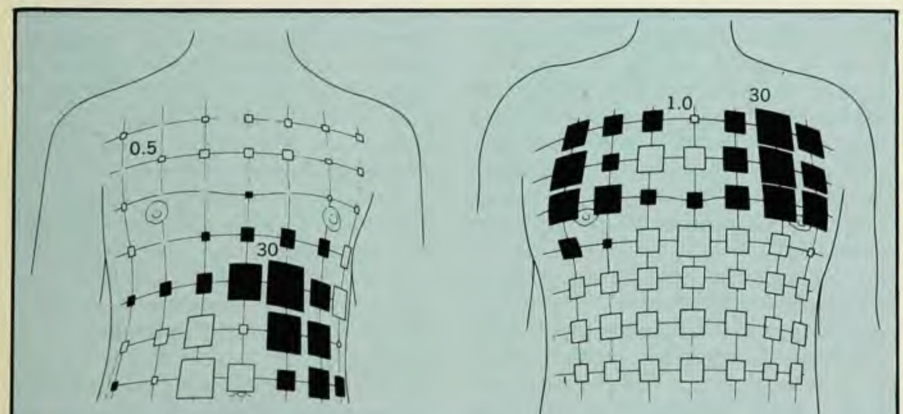
Magnetic field of the brain

The use of the EEG in extracting information from the brain is relatively limited in comparison with the increasing usefulness of the ECG in measuring the heart's electrical activity. This is due to the more complicated electrophysiology and anatomy of the brain and, for spontaneous activity of the normal brain, to the lack of a high degree of repetition such as that present in the heartbeat. The MEG therefore, may eventually have a different and more general application to the brain than that of the MCG for the heart.

My neurophysiology collaborators and I have made lengthy MEG recordings of normal states from normal brains, including the alpha rhythm[12] and the MEG during sleep. Recordings have also been made of various abnormal brain subjects including epileptics, in whom large and striking electrical events are frequent. While the alpha-rhythm MEG's do not appear to show anything unusual, the sleep and epileptic MEG's often show different features from the corresponding EEG's.

Some of the abnormal MEG's lend themselves to interpretation by simple visual inspection. Consider, for example, the MEG[12] in figure 7. Why, it may be asked are the 5-Hz theta waves, visible in the three EEG's, largely missing from the MEG? One simple explanation is that these waves were generated by a source, in the cortex, of the radial type mentioned earlier. Our examination of this patient's complete EEG supports this explanation; the theta waves show a symmetry pattern appropriate to a simple dipole generator oriented normal to the scalp. In this case, then, the MEG does not reveal new information but helps, in combination with the EEG, to determine an event that is difficult to analyze with the EEG alone.

Other events, in which the MEG may be of different use, are the steady currents in the brain, now receiving attention from neurophysiologists. These have been found to occur during some normal states of the brain as well as



Eating beans from a can and arc welding introduced ferromagnetic particles into the bodies of two subjects to produce the steady magnetic fields shown in these maps. The black squares show underlying Fe_3O_4 (about 100 micrograms in the stomach of the man on the left and about 500 micrograms in the welder's lungs) and the open squares, of opposite polarity, are the return paths of the field. The areas of the squares are proportional to the field; the largest and (nonzero) smallest values are shown in units of 10^{-7} gauss. Figure 8 during several abnormal conditions. Unlike steady currents from the heart, some of the steady brain currents have been measured with surface electrodes, although with great difficulty because of electrode–skin potentials. Because magnetic determination of these steady currents is free of these potentials, it may be the appropriate technique.

The magnetic field of the lung

Although the dc MCG has already been used as a research tool and both the MCG and MEG have clinical possibilities, the measurement of ferromagnetic particles in the lung is of more immediate use. This is due both to the stronger fields, which allow the simple fluxgate gradiometer to be used, and to the more ready interpretation of fields from particles as compared with fields from currents.

We first noted ferromagnetic particles in the bodies of animals when we began using the dc MCG to look for the steady injury current; the particles also gave rise to a steady field. Eventually it was realized that these particles were contaminants carried in through the animal's food, and that humans also receive these particles, both with food and air. The particles are easily magnetized by an external field and then demagnetized with a magnetic tape eraser. We were measuring, then, the remanent field of ferromagnetic particles situated in a viscous medium. We decided to use a magnetic map in order to display these particles visually; figure 8 shows two such maps. To produce a map, the subject is first magnetized by a field applied approximately normal to the skin; a hand-held alnico magnet or, for better uniformity, large air-core coils can be used for this. Applied fields can be in the range of 300 to 1000 gauss, beyond which there is no increase of remanent field. After the applied field is removed, the normal component of steady field is measured at regular points across the torso. This measurement is carried out in the same sequence as with the dc MCG: the subject stands away from the detector, then at the detector and then away again; the shift of baseline of the detector output is a measure of the steady field. As with the dc MCG, the steady fields from particles can be measured in the presence of the stronger steady background in the room. The data is then mapped as in figure 8, which shows that the organs can be roughly outlined by this method.[13] The weaker fields from a small amount of magnetite are best measured with the SQUID in the shielded room; stronger fields can be measured with the fluxgate gradiometer without shielding.

Measurements of Fe_3O_4 particles in the body are useful for two reasons.[13,14] The first involves asbestos: The harmful effects of asbestos dust that has settled in the lungs of workers, especially when present in large amounts, is becoming well known. Nearly all asbestos is strongly ferromagnetic and therefore detectable in the lungs by the method outlined above. The ferromagnetism of asbestos is not an intrinsic property of it, but has been traced to Fe_3O_4 particles that adhere to the asbestos fibers. When the deposit of chrysotile asbestos in the lungs of an asbestos worker is large enough, this deposit is detectable with the fluxgate gradiometer before any sign of the asbestos is visible on a chest x ray. If the ratio of magnetite to asbestos is known for the inhaled dust, a fluxgate measurement can roughly determine the mass of asbestos in the worker's lungs. I believe that this simple technique will be useful to the asbestos mining industry, where the ratio of magnetite to asbestos is large, in helping to set limits of inhaled asbestos. We have recently measured a large group of asbestos workers in the downtown section of a mining town, using a fluxgate gradiometer without shielding; magnetite was readily measured in the lungs of most workers and a correlation is now being made between the amount of magnetite and clinical data.

The second use of magnetite in the lungs is as a tracer. Disease in the lungs often progresses to a serious stage before it is detectable with present diagnostic methods, and new techniques of obtaining lung information are badly needed. The distribution, rotational state and viscosity of magnetite in the lung, measurable with a fluxgate, are of diagnostic value. We have been using about one milligram for tracer inhalation; magnetite dust, if pure, is harmless in the lung even in gram amounts.

Our study of this tracer in the lung has yielded several surprises. One of these is a phenomenon we now call "relaxation." It was noticed, after lung particles had been magnetized, that the remanent field at the chest always decreased continuously; after an hour had elapsed the field typically dropped to 15% of the original value. For any subject the relaxation curve is remarkably reproducible from day to day, but it varies from subject to subject. In particular, there is a marked difference in relaxation rate between those subjects who inhaled magnetite years ago, say during occupational exposure, and those who recently inhaled a trace amount in our lab. By now we have measured several hundred relaxation curves from dozens of subjects, and from animals. Some details of the relaxation mechanism are still not clear but we have generally concluded that the relaxation consists of small, random rotations of the magnetite particles induced by the motion of the walls of the air cells, called alveoli, in which they reside. The alveolar fluid lining is intimately involved. After the particles have been cleared for many months from the alveoli to various interstitial sites, most particles no longer have the same ease of rotation. Our study of this model has led us to believe that the relaxation rate reveals information both about the alveolar motion and about the fluidity of the alveolar tissue, and hence about possible abnormal conditions of the lung.

Potential clinical uses

The measurements described here—of the heart, the brain and the lungs—are potentially of value in clinical diagnosis and physiological research. One consideration in determining their clinical usefulness is the ease with which these measurements can be made. From this point of view the measurement of magnetite in the lung, inhaled industrially or as a tracer, seems to have the greatest potential; an inexpensive fluxgate gradiometer can be used with no shielding or, if necessary, with a movable one-layer shielded closet (as we have done). Perhaps next in line are the MCG's, both ac and dc. These need not be recorded in a room as well shielded as ours; again a simple closet can be used. The detector in this case would be a SQUID gradiometer; therefore the background would be reduced by both the gradiometer and the closet. The cost and management of this system could readily be handled by most hospitals of average size.

However, the study of magnetic fields from the human body is very new. It is still too early to tell what aspects of the body's fields will eventually be the most useful, and to predict the surprises that await us.

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