# Biomagnetism


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**Progress in ultrasensitive magnetic measurements has made it possible to study weak magnetic fields produced by the bioelectric activity of biological tissues. Such measurements are made now in biophysics and medical science and have also clinical applications.**

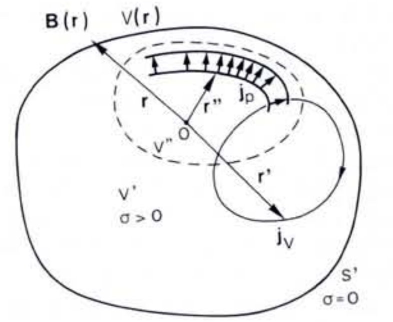




*Fig. 1 — To facilitate the calculation of bioelectric and biomagnetic fields we assume that the electric conductivity σ of a bioelectric volume conductor v' is constant and that the primary current sources $j_p$ are confined to a subvolume v''. The volume currents $j_v$ are not shown in detail.*

About two hundred years ago an Italian physician Luigi Galvani made a number of experiments on the interdependence of electricity and the contraction of the leg muscle of a frog. He noticed that some unexpected contractions occurred in synchronism with the sparking of a nearby electric instrument. In 1971, Galvani published his work *De viribus electricitatis in motu musculari commentarius*.

Alessandro Volta, professor of physics, repeated Galvani's experiments. He questioned the biological generation of electrical phenomena and in 1976 showed that only the contact of two dissimilar metals with an electrolyte was necessary for the production of electric currents. Some 30 years after Galvani's discoveries the first galvanometers became available. Evidence was then found that electric currents were produced by muscular activity and ever since, studies of such bioelectric phenomena have been very important for the basic understanding of many biological processes.

Registrations of electrocardiograms (ECG), electroencephalograms (EEG), electroretinograms (ERG) etc. are widely used in clinical practice while various types of bioelectric measurement are utilized in biophysics and medical science. The purpose of such measurements is to learn of electric currents (or potentials and charges) associated with the functioning of the biological systems studied. As is seen in Table 1, the frequencies involved are relatively low and the amplitudes of the signals in electric surface potential measurements are of the order of 1 mV or less (and about 100 mV in intracellular registrations).

Most biomagnetic fields are caused by the same current distributions that create the electric potentials in the biological volume conductor. As Table 1 shows, biomagnetic fields are weak, and small compared with the external magnetic noise. Registrations of magnetocardiograms (MCG), magnetoencephalograms (MEG), magnetoretinograms (MRG) etc. have become possible only during the past two decades. It has been proved both theoretically and experimentally that biomagnetic measurements are able to yield information on the sources which is complementary to the data obtained from electric measurements.

In Table 1, are also cited signals which are caused by pure magnetization such as ferromagnetic contamination of the lung tissue. Such phenomena naturally do not have any electric counterpart.

### The Inverse Problem

From the point of view of its electromagnetism, a typical biological specimen can be illustrated as in Fig. 1. A volume conductor of electric current *v'* is bounded by an outer surface *S'* outside which the electric conductivity is zero. The sources of electric current density $\mathbf{j}_p$ are assumed to be confined within a subvolume *v''*. The actual current sources work at the cellular level and we measure the result of their total action: either the electric surface potential $V(\mathbf{r})$ or the magnetic field $B(\mathbf{r})$ close to S'. In addition, v'' could contain material with magnetization $\mathbf{M}(\mathbf{r}'')$. The question is which information on $\mathbf{j}_p$ and $\mathbf{M}$ can be obtained from such electromagnetic measurements in a quasistatic situation.

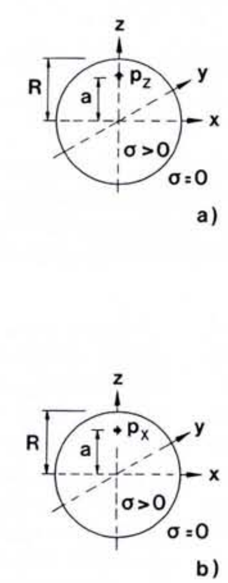
Unfortunately, the inverse problem of determining the sources of electromagnetic fields from external measurements has no unique solution. However, these quasistatic fields can be expanded into multipole contributions, whose equivalent generators are the multipole moments of the electric and magnetic multipole sources. These moments can be uniquely determined from external measurements but they do not determine the source distributions in real space. In addition, the multipole expansions are valid only outside a sphere containing all the sources of the field. In Fig.

**Table 1 — Some bioelectromagnetic phenomena, their approximate frequency bands, maximum signal amplitudes and pioneering recordings.**

| **BIOELECTROMAGNETIC PHENOMENA** | **APPR. BANDWIDTH** (Hz) | **MAGNETIC SIGNALS** | **ELECTRIC SIGNALS** |
|---|---|---|---|
| Cardiogram | 0.05 - 100 | MCG 50 pT (Baule *et al.* 1963) | ECG 1 mV (Waller 1887) |
| Fetal Cardiogram | 0.05 - 100 | FMCG 10 pT (Kariniemi *et al.* 1974) | FECG 50 μV (Cremer 1906) |
| Myogram | DC - 2000 | MMG 10 pT (Cohen 1972) | EMG 1 mV (Adrian 1929) |
| Encephalogram | 0.05 - 30 | MEG 1 pT (Cohen 1968) | EEG 50 μV (Berger 1924) |
| Evoked Potential/Field | DC - 100 | VEF 0.2 pT (Cohen 1975) | VEP 10 μV (Walter *et al.* 1946) |
| Retinogram | 0.1 - 30 | MRG 0.1 pT (Aittoniemi *et al.* 1978) | ERG 100 μV (Holmgren 1865) |
| Lung Contamination | DC | FC 1 μT (Cohen 1973) | — |
| Susceptibility Plethysmography | | MSPG (Wikswo *et al.* 1974) | — |
| Human Iron Stores | | (Harris *et al.* 1978) | — |

1, this sphere should enclose totally the volume $v'$.

In real studies of say the human body, for practical reasons, the measurements are not made outside the complete sphere because of the parasitic influences. A further problem is the inhomogeneous and often anisotropic electric conductivity of the human body. In addition, signals from other parts of the system may intefere with signals of interest. For example, in studies of some part of the human brain, interfering signals are produced by the heart, the eye and other parts of the brain whose functioning cannot be stopped during the time of the experiment! Evidently the solution of the inverse problem is difficult and is only obtained by using equivalent generators for the sources or by using a suitable simplified model for the volume conductor or both.



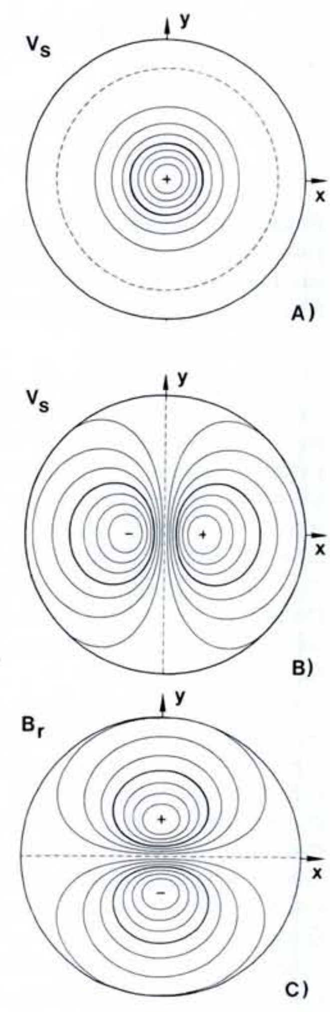




*Fig. 2 — A) and B) The electric surface potentials $V_s$ and C) the component of the magnetic field perpendicular to the surface $B_r$ produced by current dipoles in an electrically homogeneous spherical volume conductor. The maximal values (normalized) are indicated by ± signs, the thick line is the half-maximum contour line and the broken lines indicate the zero value. The small spheres (a,b) show the current sources: a) a radial current dipole $P_z$ (for A) and b) a tangential current dipole $P_x$ (for B and C). Both dipoles are located at the z-axis with $a/R = 0.7$.*

## Modelling

A starting point for a simple model is to consider the current sources such as $\mathbf{j}_p$ in Fig. 1 immersed in an infinite and homogeneous conductor. The expressions for the electric and magnetic potentials in an infinite volume are:

$$V_\infty(\mathbf{r}') = -\frac{1}{4\pi\sigma}\int_{V''}\frac{\nabla \cdot \mathbf{j}_p(\mathbf{r}'')}{|\mathbf{r}' - \mathbf{r}''|}\,dv'' \qquad (1)$$

and

$$\mathbf{A}_\infty(\mathbf{r}') = \frac{\mu_o}{4\pi}\int_{V''}\frac{\mathbf{j}_p(\mathbf{r}'')}{|\mathbf{r}' - \mathbf{r}''|}\,dv'' \qquad (2)$$

The influence of the boundaries has already been investigated by Helmholtz who considered a hypothetical potential double layer, placed at the surface $S'$ of the conductor. The double layer was chosen so as to give in a homogeneous medium outside $S'$ the same potential and currents as the source current density $\mathbf{j}_p$. Changing the sign of the double layer results in zero current density outside $S'$ and in the following expressions for the electric and magnetic potentials for bounded volume conductors:

$$V_v(\mathbf{r}) = V_\infty(\mathbf{r}) - \frac{1}{4\pi}\int_{S'} V_{S'}\,dS' \cdot \nabla\left(\frac{1}{|\mathbf{r}' - \mathbf{r}|}\right) \qquad (3)$$

and

$$\mathbf{A}_v(\mathbf{r}) = \mathbf{A}_\infty(\mathbf{r}) - \frac{\mu_o}{4\pi}\int_{S'} \sigma V_{S'}\,\frac{dS'}{|\mathbf{r}' - \mathbf{r}|} \qquad (4)$$

The use of Eq. (3) to find the surface potential V of bounded volume conductors is a nice undergraduate exercise.

For practical use, often extremely simple models have to be utilized. Consider as an example current sources in a homogeneous conducting sphere and take into account only the lowest order term of the multipole expansion. The problem is reduced to finding a current dipole in a sphere. The solution of the corresponding direct problem shows several representative features, which help in understanding the relative merits of bioelectric and biomagnetic measurements. Fig. 2 shows the contour lines of the electric surface potential and the radial component of the magnetic field.

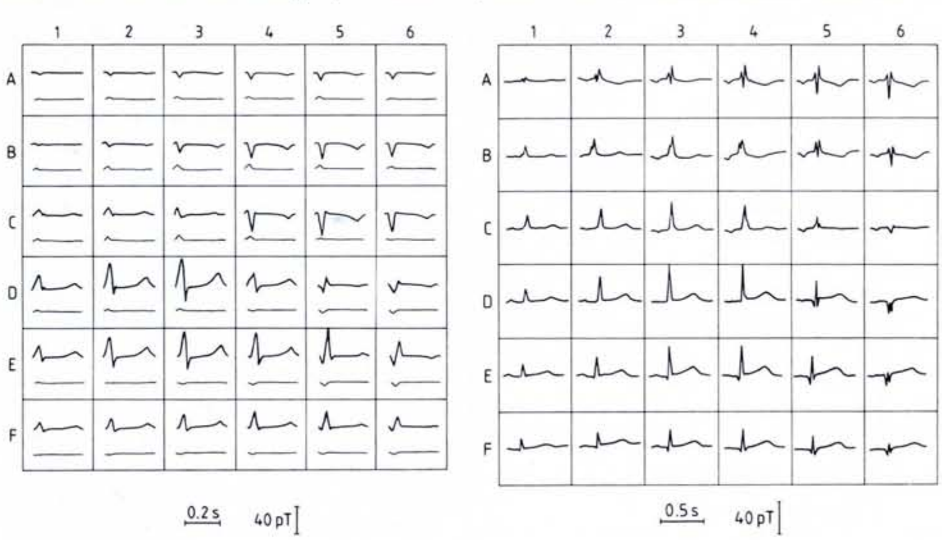



*Fig. 3 — Left, computer simulated magnetocardiograms (QRS-T morphology) in an anterolateral myocardial infarction (thick line) and the difference from the normal MCG (thin line). The measurement grid approximately covers the area of the chest of the subject. The computer program developed by D. Geselowitz and W.T. Miller (Pennsylvania State University) was used. (Siltanen P., Poutanen T., Katila T., Seppänen M., and Varpula T., Ref. 2)*
*Right an example of the measured traces of a patient with an anterolateral infarction.*

The field was chosen instead of the magnetic potential, since it is closer to what is measured in practice.

The following features which are valid exactly in our ideal case are also approximately valid for many real measurements:

— Both radial and tangential current sources contribute to the electric surface potential.
— The external magnetic field is caused solely by the tangential current sources.
— Current sources close to the surface create potentials at the surface which are higher by a factor of two than would be measured if we were dealing with an infinite volume conductor. Surface potentials caused by current sources close to the centre are magnified by a factor of three.
— In the radial component of the magnetic field, the second term of Eq. (4) is equal to zero. This can be generalized as follows: The component of the magnetic field perpendicular to the surface is least affected by volume currents, or in other words: concentric electric inhomogeneities to which the skull around the brain approximates often have no effect on the external magnetic field.
— Deep sources produce relatively weak magnetic fields. Thus it seems that biomagnetic measurements trace effectively the superficial current sources only.
— The distributions of the electric potential and of magnetic field reveal information on their sources, which with suitable simplifying assumptions can be used to localize the sources and to estimate their magnitudes. For superficial and tangential sources the surface potential and the radial component of the magnetic field seem to show similar contour lines and spatial resolution. The field patterns are oriented perpendicular to each other.

The direct problem, i.e. to calculate the fields from the sources assumed, can be solved if the geometry is known. Very advanced computer models have been developed for this in cardiography. Computer programs are able to calculate the distribution of the surface ECG and MCG field components outside the human torso for standard torso geometry and bioelectric activation. The influence of abnormalities in the functioning of the heart can often be taken into account. Fig. 3 shows an example. It is the calculated map of the component of the MCG field perpendicular to the frontal plane for an (anterolateral) myocardial infarction. The figure also shows the calculated difference of the actual MCG from the normal MCG. The same program can be used to calculate the surface ECG as well.

**Measurement Techniques**

The magnetometers used for measuring biomagnetic fields must be sufficiently sensitive yet able to reject the very much stronger "common mode" magnetic background noise. Although some conventional magnetometers, such as fluxgate or ordinary induction coil magnetometers, have been successfully used for measurements of biomagnetic fields they are generally not sensitive enough. Baule and McFee (1963) used in their pioneering work on magnetocardiograms two identical and parallel coils, two million turns each, wound oppositely on ferrite cores. Today parametric Superconducting Quantum Interference Device (SQUID) amplifiers are mainly used. A closed loop of superconducting wire transfers magnetic flux to the SQUID even in DC operation without contributing thermal noise.

Since external magnetic noise is such a serious limitation on studies of very weak magnetic fields, a magnetically shielded chamber provides an optimal solution. A shielded chamber large enough for human subjects with three layers of high-permeability ferromagnetic material and additional eddy-current shields has been successfully used by D. Cohen at M.I.T. (Boston) since 1971. The shape of the chamber approximates a sphere. A number of rectangular chambers have been constructed (e.g. recently at the Helsinki University of Technology and at the Physikalisch-Technische Bundesanstalt, West Berlin). Field noise as low as $3fT/\sqrt{Hz}$ has been measured with a SQUID magnetometer at about 10 Hz in the PTB-chamber. Such a level allows direct field recording of most biomagnetic signals. Nevertheless, differential flux transformers (gradiometers) are most often used instead of a single coil. One coil then acts as a reference and the other oppositely wound coil as the actual signal coil.

Most research groups do not have a magnetically shielded chamber available. One solution to the problem of magnetic noise is to perform the measurements outside the laboratories on a magnetically quiet measurement site. "Nonmagnetic" cottages situated in suburban areas are used by several groups. Then a first order gradiometric measurement can be used to obtain high quality data. However, a balance of the gradiometer at the 10 ppm level is necessary to compensate for long-range magnetic noise which is usually between $10^3$ and $10^5$ $fT/\sqrt{Hz}$ at the frequencies of interest. Naturally, the measurement also contains a DC-background, since the Earth's steady magnetic field is some $10^9$ times stronger than the weakest biomagnetic fields measured.

For clinical applications a remote measurement site is not feasible and measurements in a laboratory or in a hospital without a magnetically shielded chamber are even more problematic. The magnetic field at the main line frequency may easily reach a value of 10 nT and the low frequency noise several hundred nT peak to peak during 10 s. The usual answer to these constraints is a second order gradiometer (Fig. 4) very accurately balanced. With proper filter-

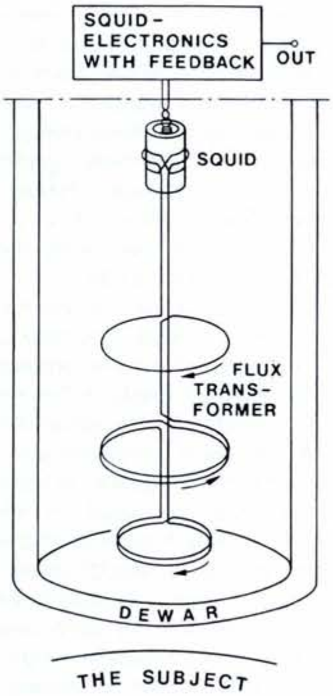



*Fig. 4 — A second order asymmetric gradiometric flux transformer, coupled to an RF-SQUID amplifier. The SQUID and the flux transformer must be immersed in liquid helium to maintain the superconductivity.*

ing techniques and suitable data processing the standard band 0.05 - 100 Hz may show a sensitivity of the order of 40 fT/$\sqrt{}$Hz with some 1/*f* contribution at the low frequency tail.

The most often used SQUID so far is the 2-hole Zimmerman-type RF-SQUID. The weak link in such a SQUID used to be the screw point contact, but recently, modifications to the design have resulted in very reliable low noise amplifiers. Field sensitivities around 10 fT/$\sqrt{}$Hz have been reported. The new DC SQUID designs should allow field sensitivities still better by about a factor of ten. To utilize fully such sensitivities much attention must be paid to the noises produced by the liquid helium dewar in which the gradiometer is immersed and to the external magnetic noise. The unavoidable use of some, albeit simple, low temperature techniques complicates the measurements in two ways. First, liquid helium is rarely in routine use outside physics laboratories and its handling requires some extra training. Second, the liquid helium dewars are large, unwieldy containers that cannot be tilted arbitrarily.

**Results**

The pioneering observation of Baule and McFee started magnetocardiographic measurements twenty years ago. The electric activation sequences of the normal heart and many abnormal cases are reasonably well explored. Morphological maps such as that in Fig. 3 can be calculated using computer simulation programs. It appears that the morphologies of the MCG and ECG waveforms resemble each other. It is possible to identify deflections which are associated with atrial and ventricular depolarizations etc. The present signal-to-noise ratio of the MCG measurements, about 40 dB, is of the same order of magnitude as that of conventional ECG measurements. However, the MCG so far has not really been applied in clinical practice although its diagnostic power appears to be very similar to ECG, and the method is contactless and thus especially suitable for mass screening. The reasons are mainly the technical difficulties mentioned above.

In ECG, high resolution surface potential measurements have been performed to observe the much smaller signals of the conduction system of the heart, late ventricular potentials, and fetal ECGs. All these signals have been seen in magnetic measurements as well, and are presently studied by several research groups. In addition, it has been possible to detect by magnetic methods injury currents which are difficult to measure electrically. The MCG thus offers definite advantages, but further research is still needed in order to clarify the relative merits of the ECG and the MCG.

On the cellular level, simultaneous electric and magnetic measurements yield complementary information on the potential and current distributions e.g. of the action potential of a nerve. J.P. Wikswo *et al.* at Vanderbilt University (Nashville) were able to measure the magnetic field of isolated axons. The magnetic field data provide more direct means to study the currents than the electric measurements. On the other hand SQUID-measurements are more limited due to the large size of present magnetometers and their still relatively low sensitivity.

Electroencephalographic (EEG) studies of the human brain are widely used both for basic brain research and for clinical applications. In practice the electric potential distribution caused by a dipolar source is not as sharp as in the example of the homogeneous spherical volume conductor of Fig. 2. The electric inhomogeneities due to the liquor spaces, skull and scalp smear considerably the potential distributions, while the magnetic field is less affected. Therefore, magnetoencephalographic (MEG) measurements are suited for localizing cortical electric activity. Again there are limitations: the magnetic field sees the tangential part of cortical sources only and deep dipoles in a homogeneous medium contribute very little. A synchronous collective action of numerous neurons is required to see the signal above noise. The simultaneous activity of several cortical areas complicates the interpretation of spontaneous EEG and MEG. Nevertheless, success in localizing epileptic activity e.g. has been obtained using magnetic methods.

In studies of evoked electric potentials, a suitable external stimulus is repeated several times; the time averaging improves the signal-to-noise ratio by decreasing the level of the nonsynchronous background activity. In Fig. 5 we see examples of auditory evoked electric potential and magnetic field recordings. The stimuli are binaural tones at 1 kHz. Both signals show prominent deflections at latencies about 100 ms and 200 ms after the stimuli and sustained (SP/SF) contributions. The spatial distributions of the amplitudes of various deflections are measured and simple current dipole models, such as that shown in Fig. 2 are used to localize the equivalent current source. More accurate information on the sources could naturally be obtained from intracranial recordings and from animal studies. However, not all deflections show up in animals and studies during neurosurgical operations

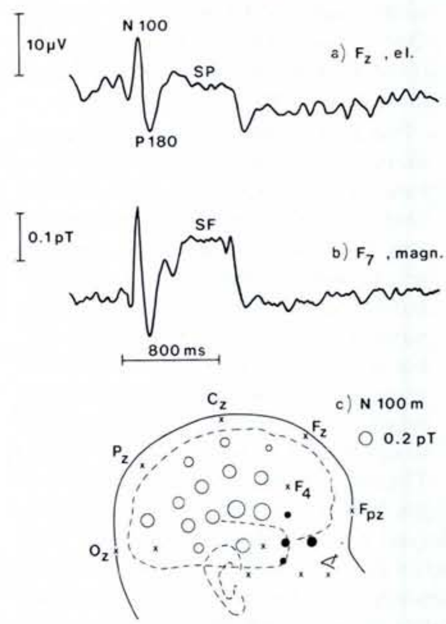



*Fig. 5 — Electric and magnetic auditory evoked responses. The stimulus was a 1 kHz sound, 800 ms in duration. a) Average of 87 electric responses. b) Average of 330 magnetic responses. c) The distribution of the amplitudes of magnetic N 100 responses. The component of the magnetic field perpendicular to the skull was measured. Open circles indicate magnetic flux into the skull (Hari R., Aittoniemi K., Järvinen M.-L., Katila T. and Varpula T., Exp. Brain Res. 40 (1980) 237).*

are of course limited for other reasons. The magnetic measurement technique, often augmented with electric surface measurements has helped in localizing a number of source activities in the cortex, elicited by stimuli of different modalities. The studies made at New York University especially deserve to be mentioned. Although the evoked magnetic fields are only a few hundred femtotesla in amplitude, they were successfully measured without any magnetic shielding!

It would not be appropriate to list here all possible applications of biomagnetic measurements. Instead we shall finish by mentioning the studies of magnetic biosusceptibility or magnetization *in vivo*. The mechanical activity of the heart produces an induced signal in the external magnetic field. Excess iron in liver has been detected by a group at Case Western Reserve University using a similar technique. Several groups have studied the accumulation of magnetic contamination in the lungs of welders. The subjects were magnetized in an external magnetic field and the remanence magnetization was measured. Often these fields are so high that conventional flux-gate magnetometers can be used.

#### REFERENCES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3. *Biomagnetism*, Eds. S.J. Williamson, G.L. Romani, L. Kaufman and I. Modena (Plenum Press, New York) 1983.


## EPS History

We apologise for the ommission of a line in the President's article in May. To set the record straight, the sentence dealing with the early days of EPS should read:
"At the time of the inaugural conference in Florence in April 1969, following the establishment of the Society in Geneva in September 1968..."

## Delegates of Associate Members

Following the recent ballot, the delegates to Council of the Associate Members are:

E. Feldtkeller, Siemens (4 years)
J.-C. Lehmann, CNRS (4 years)
R.W. Brander, British Telecom. (2 years)
J.A. Goedkoop, ECN (2 years)