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Remote detection of human electroencephalograms using ultrahigh input impedance electric potential sensors

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In this letter, we demonstrate the use of very high performance, ultrahigh impedance, electric potential probes in the detection of electrical activity in the brain. We show that these sensors, requiring no electrical or physical contact with the body, can be used to monitor the human electroencephalogram (EEG) revealing, as examples, the α and β rhythms and the α blocking phenomenon. We suggest that the advantages offered by these sensors compared with the currently used contact (Ag/AgCl) electrodes may act to stimulate new developments in multichannel EEG monitoring and in real-time electrical imaging of the brain. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1516861]

Electrical activity in the human brain was first reported in 1929 by Hans Berger[1] who recorded the electrical potential variations from the scalp and introduced the term electroencephalogram (EEG) to describe the graphical time domain signal resulting from these changes in electrical potential. Since Berger's seminal work, great advances have been made in the amplification, electronic processing, and real-time display of EEG signals. These advances, aided by the recent introduction of computer-based techniques for signal recognition and manipulation, have led to the EEG becoming an invaluable tool in the diagnosis of many neurological illnesses.[2] Despite these advances in signal quality, the practical convenience of collecting EEGs is still limited by the traditional sensor techniques used to detect brain electrical activity. In special cases, this activity has been recorded by means of electrodes in contact with the surface of the exposed brain (i.e., with a portion of the skull bone removed and by using depth electrodes where subcutaneous needles are inserted into the exposed brain tissue). However, for conventional clinical analysis, the EEG is recorded using electrodes that are in real charge current contact with the scalp tissue. In practice, this is provided by an Ag/AgCl electrode used in conjunction with an electrolytic paste. These act together to form an electrical transducer to convert the ionic current flow in the skin into an electron flow which can then be detected by an electronic amplifier.[3] In this, the electrolyte performs the dual role of a conducting paste and a glue to anchor the electrode to the scalp. In preparation, the scalp has to be cleaned which usually involves the shaving of hair and abrasion of the skin—a process that is both uncomfortable to the subject and which also has a tendency to lead to unreliable electrical contact.

In the past these problems have been circumvented, at least at the research level, by the use of superconducting quantum interference device (SQUID) magnetometers[4] to detect the magnetic rather than the electric component of the fields generated by the flow of currents in the brain. While SQUID magnetometers can have quite sufficient sensitivity to follow these magnetic signals (magnetoencephalograms—MEGs)—and remotely, off head—they carry with them certain drawbacks. The most obvious is cryogenic operation. However, there is also the general requirement for magnetically shielded environments, always a very expensive consideration. In addition, the need to run in feedback lock due to the inherent piece-wise linear response of SQUIDs, and the difficulty of summing signals electronically from two or more SQUID systems, are also factors which must be considered. These problems can be avoided, while remote operation is maintained, if we make use of the recently developed room temperature, ultrahigh input impedance, electric potential sensor for EEG[5] rather than MEG detection.

This sensor operates using electric displacement, rather than real charge, current. It therefore does not require real electrical contact to the signal source (e.g., the human body) in order to function. This overcomes the disadvantages of conventional Ag/AgCl electrodes while still maintaining sufficient sensitivity (70 nV/$\sqrt{}$Hz at 1 Hz noise floor)[6] to detect body electrical signals off body. This development clearly can be very advantageous in detecting the electrical activity within the brain since, being truly noninvasive, it should be possible to operate this sensor without removing scalp hair and without any direct electrical contact to the scalp. We have previously reported on the use of such low noise, ultrahigh impedance, electric potential sensors in the detection and recording of very high quality electrocardiograms (ECGs) with no electrical contact to the body.[6] Furthermore, using similar techniques, we have been able to record the human heartbeat at distance up to 1 m off body with no electrical connection between the sensor and the body.[6] In this letter, we demonstrate that we now have the sensitivity to detect EEGs through the scalp hair with no electrical contact to the scalp. We also show that it is now possible to detect brain electrical activity with an air gap between the scalp hair and the sensor.

A block diagram of our electric potential sensor design is shown in Fig. 1. As can be seen, it consists[6] of a probe electrode coupled to an electrometer amplifier whose input impedance, off dc, has been enhanced very substantially us-

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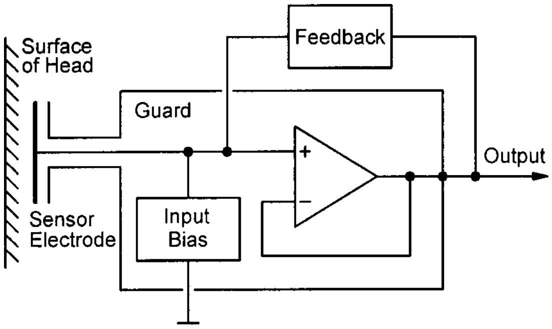

FIG. 1. Block diagram of a typical EEG electric potential sensor in remote off-body mode showing the probe electrode (disk of diameter 1 to 2 cm), feedback, guard, and input bias circuits of the electrometer amplifier.

ing feedback techniques. For the work described in this letter, a generic electric potential sensor has been designed for use with an air gap between the source and the probe electrode. We refer to this air gap embodiment as the remote off-body mode. We can modify this design very easily so that the electrode probe is in mechanical, but not electrical, contact with the source. This allows for stronger coupling and, in some cases, the advantage of mechanical stability. We term this the contact mode. In this mode, the EEG probe electrode is a disk with a typical diameter in the range 1 to 2 cm. In the block diagram of Fig. 1, the electric potential sensor is shown in the remote off-body mode of operation with no electrical or physical contact to the head. However, for the results presented in this letter, we have used both the contact and remote modes of operation. In practice, we have tended to locate our sensors, usually used differentially in pairs, in a specially designed helmet.

An illustration of the application of the electric potential probes to the detection of electrical activity from the brain is shown in Fig. 2. Here, we provide an example of an EEG differentially recorded from the posterior of the head in the region of the occipital lobe (P3 and O1 positions according to the International 10–20 system of EEG electrode placement)[7] using two sensors with 25 mm diameter probe electrodes in contact with the scalp hair. In Fig. 2(a) we show the alpha rhythm signal which is present in the occipital region of the brain when the subject's eyes are closed. When the eyes are open the alpha rhythm disappears, replaced by the beta rhythm. We note that no special preparation was made to the scalp, the signals simply being collected through the scalp hair. Frequency domain plots generated from the EEG are shown in Fig. 2(b) with eyes closed and eyes open time periods displayed. The prominent peak at approximately 9 Hz in the eyes closed period is due to the alpha rhythm. It is well known that the alpha rhythm (8–14 Hz) is most prominent when the subject is at rest with the eyes closed. However, when the eyes are opened, this rhythm usually disappears, being replaced by beta rhythms (14–35 Hz)—a phenomenon called alpha blocking.[8] This was originally observed by Berger.[1] The observation of this alpha blocking phenomenon is used here as evidence that a high-quality EEG is in fact being monitored.

The high quality of the signals detected using this simple, noncontact technique is further illustrated in Fig. 3. Thus, in Fig. 3(a) we present another time domain set of EEG data, similar to that shown in Fig. 2, but for a longer period showing successive eyes closed/open states, the change of state being denoted, as in Fig. 2, by event markers. These data were collected through the scalp hair from the posterior of the head and again demonstrate the phenomenon of alpha blocking. More information can be obtained if a form of frequency domain plot is made. In Fig. 3(b), we show the data of Fig. 3(a) presented as a joint time–frequency (JTF) display.[9] In this JTF plot, it is quite apparent that in the eyes closed period, the EEG is dominated by an alpha rhythm at around 9 Hz which disappears when the eyes are opened.

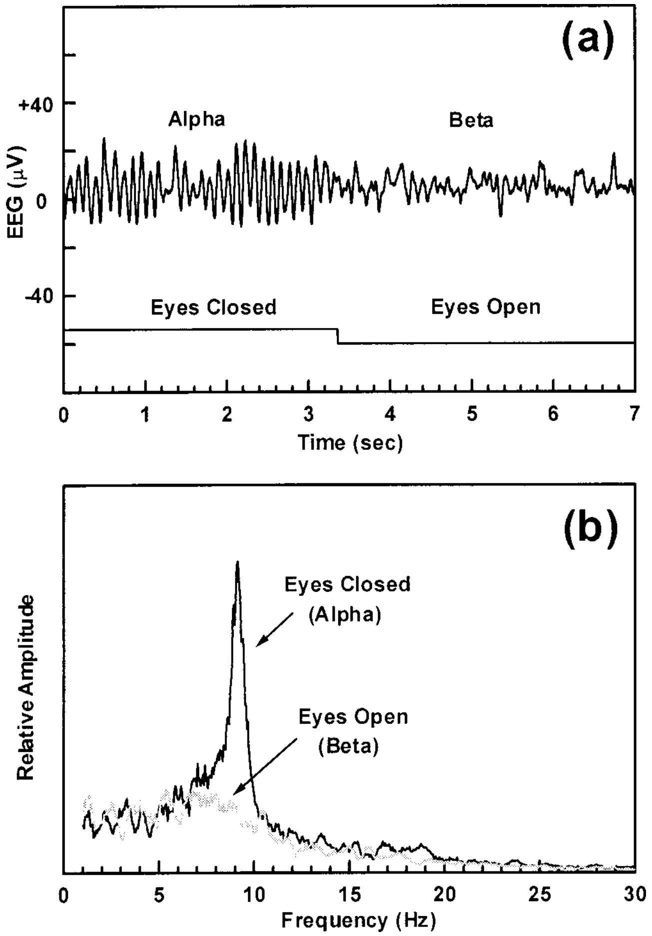

FIG. 2. EEG data collected through hair from the posterior of the head using two sensors differentially (P3 and O1 positions). (a) Time domain signal showing the alpha rhythm (eyes closed) changing to the beta rhythm (eyes open). (b) Power spectra in the frequency domain for alpha and beta rhythms.

In previous work,[5,6] we described the way in which electric potential sensors could be used to measure the ECG off body with an air gap between the sensor probe and the chest. For the case of EEGs, it is well known that electrical activity occurs at various depths within the brain. It is also known that in the standard technique for EEG acquisition, involving the use of pasted electrodes on the surface of the scalp, the sources of this activity generate spatially complex field distributions which are averaged and distorted by the measurement process. As with ECGs, this distortion is due to the electrical loading of the body source by the currently used (relatively low input impedance) sensors. This distortion can be eliminated by the use of ultrahigh input impedance electric potential sensors so as to acquire accurate electric poten-

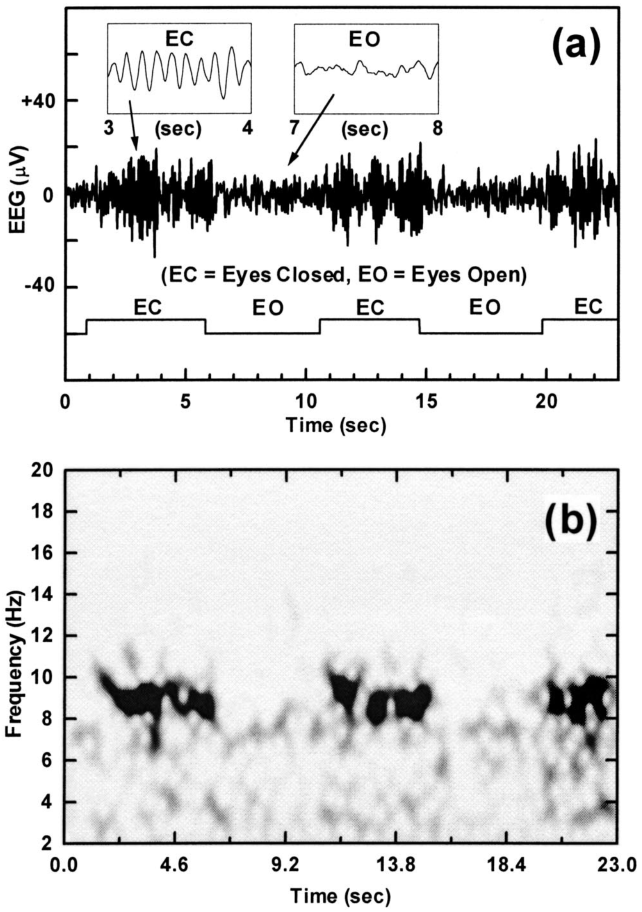

FIG. 3. Through hair P3-O1 differential EEG data (as for Fig. 2) showing the alpha blocking phenomenon. (a) Time domain, eyes closed/open, EEG signals showing clear changes in amplitude between these two eye states. (b) JTF plot for the same data where the black regions correspond to peaks in alpha activity at around 9 Hz.

tial information off head (i.e., with an air gap between the scalp and the sensor). Provided a technique is available to measure this potential at varying distances and orientations from the head, it should therefore be possible to reconstruct the source(s) of this activity by solving the inverse problem. That the electric sensor capability now exists to start such a program of development is demonstrated by the data presented in Fig. 4. Here, we show a time domain EEG collected from two sensor probes positioned (P3-O1) with a 3 mm air gap between the scalp hair and the sensors, i.e., with no mechanical or electrical contact to the head. Again, the alpha rhythm is blocked [Fig. 4(a)] when the eyes are open. This is very clearly shown in the frequency domain fast Fourier transform plots of Fig. 4(b) where the alpha rhythm peak dominates the broad spectrum of the beta rhythm.

From the data presented in this letter, it would appear that the technical means are now available to create convenient, noncontact arrays of sensors for EEG monitoring and imaging of the electrical activity of the brain. As indicated by the results shown in Fig. 4, in principle, it should also prove possible to acquire electric potential information spatially distributed at various distances off head, the first step in solving the inverse problem. Given that there is still much scope for improvements in sensitivity, input impedance, and size of electric potential sensors, we anticipate rapid development and exploitation of these devices in the field of brain research and diagnostics in the near future.

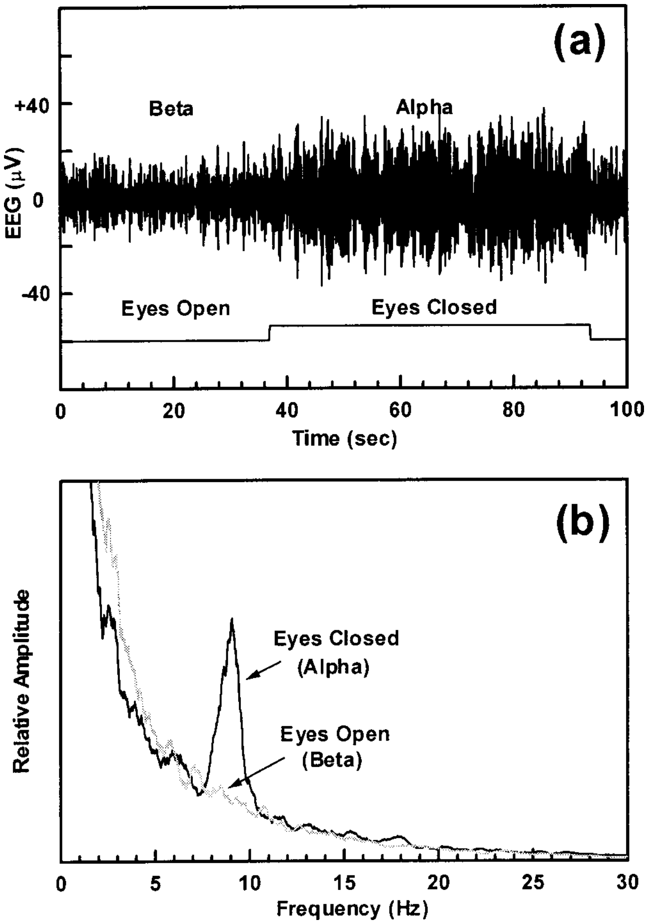

FIG. 4. Differential, two sensor (P3-O1), EEG data with a 3 mm air gap between the scalp hair and the sensor electrodes (no mechanical or electrical connection to the head) demonstrating the alpha blocking phenomenon. (a) Time domain signal showing clear changes in waveform amplitude between these two states. (b) Frequency domain plots showing the power spectra for eyes closed/open states.

[1] H. Berger, Arch. F. Psychiat. **87**, (1929); see also *Hans Berger on the Electroencephalogram of Man.*, edited by Pierre Gloor (Elsevier, Amsterdam, 1969).

[2] B. J. Fisch, *Spehlmann's EEG Primer* (Elsevier, Amsterdam, 1991).

[3] *Medical Instrumentation—Application and Design*, edited by J. G. Webster (Wiley, New York, 1988).

[4] M. Hoke, in *SQUID Based Measurement Techniques in the Art of Measurement*, edited by B. Kramer (VCH, Braunschweig, 1988).

[5] R. J. Prance, A. Debray, T. D. Clark, H. Prance, M. Nock, C. J. Harland, and A. J. Clippingdale, Meas. Sci. Technol. **11**, 1 (2000).

[6] C. J. Harland, T. D. Clark, and R. J. Prance, Meas. Sci. Technol. **13**, 163 (2002).

[7] J. Malmivuo and R. Plonsey, *Electroencephalography in Biomagnetism—Principles and Applications of Bioelectric and Biomagnetic Fields* (Oxford University Press, Oxford, 1995).

[8] A. C. Guyton, *Structure and Function of the Nervous System* (Saunders Philadelphia, 1976).

[9] S. Qian and D. Chen, *Joint Time-Frequency Analysis* (Prentice-Hall, Englewood Cliffs, N.J., 1996).