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*Research Note*

# Magnetic Fields of the Human Brain Accompanying Voluntary Movement: Bereitschaftsmagnetfeld*

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**Summary.** A slow magnetic field shift has been detected in the human brain occurring in the foreperiod of a voluntary finger movement. This magnetic field accompanies a slow negative electrical cerebral potential which occurs in the same foreperiod, the Bereitschaftspotential (BP) of Kornhuber and Deecke. The present report is the first of a magnetic field associated with the BP, and has been named the Bereitschaftsmagnetfeld (BM) or readiness magnetic field. The BM is oriented with the field lines directed out of the head in the pre-rolandic region and with the field lines directed into the head in post-rolandic areas, suggesting a source in the sensorimotor area for the contralateral hand. Distribution of the magnetic fields has so far not revealed a source in the fronto-central midline where the BP is recorded maximally. The time course and morphology of the BP and BM are similar, but they have different topography over the skull.

**Key words:** Bereitschaftsmagnetfeld – Readiness potential – Cerebral motor preparation – Source detection – Voluntary movement – Superconducting Quantum Interference Device

Electrical recordings of the cerebral potentials accompanying voluntary movement in man are well established and are being widely used in the investigation of human volitional motor preparation (Kornhuber and Deecke 1965; Deecke et al. 1976). A slow bihemispherical negativity over precentral and parietal areas and the midline, the BP, starts about 1 s prior to the onset of muscle contraction and reaches an amplitude of 5–10 μV with finger movements. Prior to unilateral movement, the precentral BP becomes asymmetrical in the later foreperiod giving way to a contralateral preponderance of negativity (CPN) about a half second prior to the movement, sometimes earlier. The BP is followed by a further bilateral smaller potential, the pre-motion positivity (PMP), with an onset time of about 90 ms and a typical distribution over the parietal cortex and the fronto-central midline. Like the CPN, the third potential, the negative motor potential (MP), is also unilateral with unilateral movement. It is restricted to the contralateral precentral motor cortex and starts about 50–60 ms prior to the onset of the first electrical muscle activity. After the onset of movement, a negative N1 component (latency 70–200 ms) and a late positive component (latency 250–450 ms) basically constitute a proprioceptive movement-evoked potential.

These electrical recordings, however, have some limitations. For example, they permit only relative interpretations since they have to be referred to an "indifferent" electrode and the propagation of electrical fields resulting from volume currents is influenced by different conductivities of the tissues overlying the source. These and other limitations make it difficult to establish intracranial sources of these electrical potentials, using measures of potential differences between the active and indifferent electrodes.

Electrical fields are accompanied by magnetic fields which may be more advantageous for source localization. It is only relatively recently that the technology became available for the measurement of minute magnetic fields generated in the human brain by intrinsic rhythms (Cohen 1972) or evoked by stimuli (Brenner et al. 1975). Advantages of this

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method over conventional electrical recording include the possibility of sensing intracerebral sources at specific locations without distortion by the conduction properties of cranial tissues and without the problems of interpretation caused by an indifferent electrode.

## Methods

The device used in the experiment for recording magnetic fields was a newly developed SQUID 3rd order spatial gradiometer manufactured by CTF Systems, Inc., Port Coquitlam, British Columbia, Canada. "SQUID" is an acronym for Superconducting Quantum Interference Device. As with all other magnetometers presently used for recording magnetic fields of the brain, the basic principle of operation is that the SQUID senses the electrical current induced by a magnetic field in a superconducting pickup coil positioned at the subject's scalp. Gradiometers feature additional coils wired in opposition in the same circuit which are located at a slightly greater distance from the subject and therefore allow the rejection of common-mode fields produced by distant sources. On the basis of theoretical analysis and computer simulation studies the present third order gradiometer was designed and constructed (Vrba et al. 1982). In this instrument the four axially-symmetric coils, each of which have from one to four windings, are separated by a distance of 5.5 cm. The pickup coil positioned closest to the source has a diameter of 3.8 cm and the other three are twice that diameter.

All recordings were done in an unshielded laboratory, in which the total magnetic noise of both the instrument and the environment was measured at about 30–50 femto Tesla rms/$\sqrt{Hz}$ above 0.5 Hz. For lower frequencies (f) noise levels increased by 1/f (Vrba et al. 1982; Weinberg et al., in press).

In the present experiment movement-related magnetic field changes were recorded and compared with the corresponding electrical recordings using three right-handed subjects. Magnetic fields were recorded from different positions over the head in successive blocks of 80 trials. Averages of the first and second 40 trials of a block were also computed to establish the reliability of the results at each position. EEG was always recorded simultaneously as a monitor for the consistency of the BP. The subject sat in a non-magnetic chair, fixated on a designated point and performed self-paced volitional flexions of the right fingers (metacarpophalangeal joints II–V). The surface electromyogram (EMG) served as the trigger and was bipolarly recorded from the right superficial flexor digitorum muscle. Electroencephalographic (EEG) recordings were taken from positions C3, C4, and Cz (international EEG 10–20 system), and the electrooculogram (EOG) from the lower orbital ridge. EEG and EOG were referred to a linked ears or mastoids reference. The sensing coil of the SQUID gradiometer was positioned approximately normal to the scalp for each recording location. An EEG electrode was not affixed at C3, C4 or Cz when MEG (magnetencephalogram) was recorded from the same position. MEG, EEG, EOG, EMG and respiration were recorded with a Siemens Mingograph (bandwidth 0.03–15 Hz, EMG 5–70 Hz) and averaged using a PDP 12 laboratory computer. A total of 256 points were sampled over an epoch of 3 s, starting 2.25 s before EMG onset. Artifact-contaminated trials were rejected on line by the experimenters.

Great care was taken to guard against MEG artifacts produced by head displacements. The subject's chair was specially constructed in the form of a dentist's chair using wood, rigid plastic foam, and no upholstery. The head rest was molded to closely fit the contours of the back and sides of the head. The arm was supported at the wrist and elbow by an arm rest separated from the chair. Head displacements were measured throughout all experimental sessions by means of a strain gauge activated by tension in a rayon cord attached to the subject's head at approximately 2 m

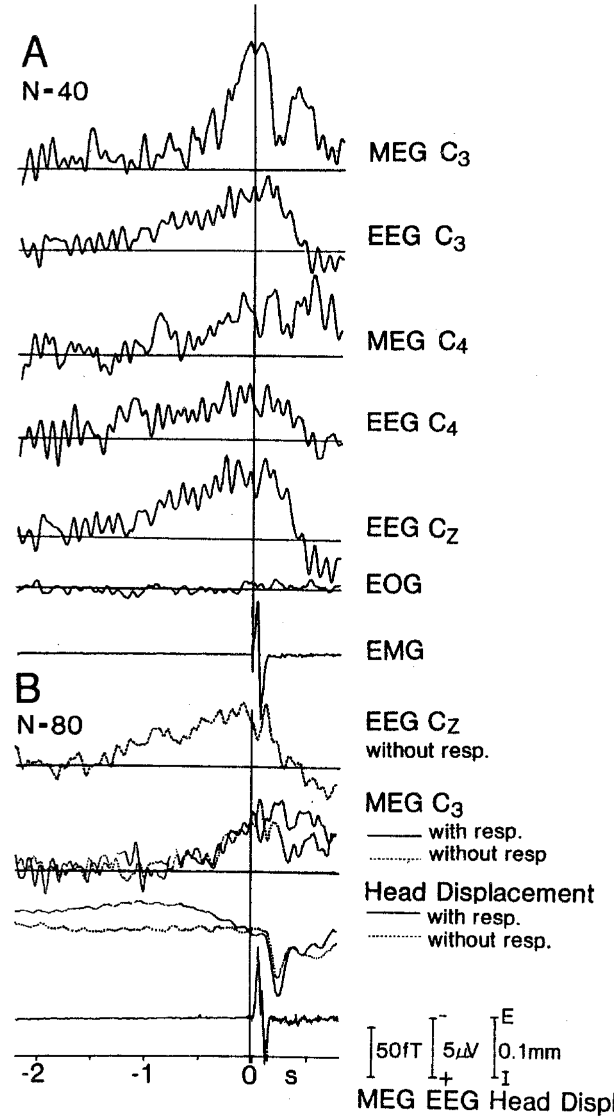


**Fig. 1A, B.** Averaged magnetoencephalographic (MEG) and electroencephalographic (EEG) recordings accompanying finger movement. Subject L.D. **A** Typical experiment showing left precentral (C3) and right precentral (C4) MEG and corresponding EEG recordings, vertex EEG, electrooculogram (EOG) and electromyogram (EMG) for 40 self-paced finger flexions. C3 MEG and C4 EEG were recorded simultaneously, as were C4 MEG and C3 EEG. Upward deflection in the MEG corresponds to magnetic field lines directed out of the head. Note the larger BMs at the left than the right precentral positions. **B** Control experiments with normal respiration (*solid curves*) and without respiration (*dotted curves*) i.e. the subject held his breath for several seconds prior to, during, and after finger movements. Vertex EEG recorded without respiration only. Head displacement measured with a remotely positioned strain gauge. Expiration (E) caused small invisible anteversion (upward), inspiration (I) retroflexion of the head. The finger movement caused small phasic retroflexion of the head after the onset of movement. Note the normal BM and BP also in the absence of respiration distance. This system was calibrated by tying the cord to the pen of an X-Y plotter which could produce accurate displacements of 0.25 mm.

## Results

The results showed that the BM could be consistently recorded over the C3 location as a typical slow deflection and indicated magnetic field lines directed out of the head (Fig. 1A). The BM had basically a similar waveform as the BP. Over the C4 location, we observed BM deflections in the same direction as those observed at C3, although smaller. Our strain gauge recordings of head displacement revealed that minute movements of the head were time-locked to respiration (Fig. 1B). Suspension of respiration commonly occurs with delicate manipulations. In this experiment, if the subject would tend to make the movement at a certain phase of respiration this could produce slow BM-like shifts in the MEG due to head displacement as well as R-wave artifacts (Grözinger et al. 1974). Various attempts to stabilize the head did reduce head movements, but did not eliminate them. Therefore, subjects were instructed to initiate a movement only after they held their breath for several seconds. In these experiments, a normal BM and BP were recorded (see Fig. 1B). All the other results presented were therefore obtained in experiments in which subjects held their breath.

In a first topographical account of the BM prior to right-sided finger movements a reversal in the direction of the BM was discovered. As is seen in Fig. 2, recordings over left pre-rolandic positions showed an upright deflection of the BM indicating field lines directed out of the head, whilst recordings over left post-rolandic positions showed a downward BM deflection indicating field lines into the head. Thus, the hand area of the sensorimotor cortex in the rolandic region is a possible source of the observed fields. At the right pre-rolandic position C4, a BM directed out of the head was found similar to that found at C3 but smaller in amplitude. The topographical results in the other subjects were similar.

In the lower right of Fig. 2, the two MEG recordings important for the reversal, C3 and C1/P1 (half way between C1 and P1) obtained in different blocks of trials are shown along with the simultaneous Cz EEG recordings in order to document consistency of shape and amplitude of the BP.

## Discussion

This is the first report of slow magnetic field changes in the foreperiod of voluntary movements. Okada et al. (1982) described premovement magnetic fields occurring 50–60 ms preceding movements which were in response to visual stimuli. The fields they reported correspond in time to the motor potential as distinct from the Bereitschaftspotential. We have suggested the term Bereitschaftsmagnetfeld (BM) or readiness magnetic field for these slower field changes.

The 3rd order SQUID gradiometer is able to measure these slow changes because the onset of 1/f noise was as low as 0.5 Hz. Great pains were taken to eliminate head displacements caused by respiration and finger movements, the latter resulting from mechanical translation of vibrations through the body. The latter occur only during the movement, but the former occur also prior to movement. Controls for head displacement proved extremely difficult since movements as small as 0.1 mm produce significant artifact in the MEG. Our strain gauge measurements revealed the importance of measuring head displacement when measuring any movement-related cerebral magnetic fields.

The importance of these initial experiments is the demonstration that the Bereitschaftsmagnetfeld can be recorded and that it apparently shares the basic morphology of its electrical analogue. The topography of the two phenomena, preceding right-sided finger movement, however, differs. Whereas the BP distribution is widespread over both hemispheres and over the midline, the BM is more sharply localized and shows a left-hemisphere reversal. It is recorded with field lines directed out of the head at pre-rolandic sites and with field lines into the head at post-rolandic sites. This finding is compatible with the assumption of a source in the hand area of the rolandic region. The limited amount of data so far available for C4 suggest that there is a similar BM of smaller amplitude over the ipsilateral rolandic area.

Also of interest is the finding that the topographical distribution of the BM is not the same as that of the BP, for which maximum amplitude is recorded over the midline, which is presumed to derive from the supplementary motor area (Deecke and Kornhuber 1978; Lassen et al. 1978). The MEG recordings done so far over the midline showed only relatively small BM deflections directed into the head (Fig. 2). A dipole source on the mesial cortical surface could have a radial orientation which would prevent it from being seen in the MEG. Experiments are now underway employing more sophisticated finger movements which may need stronger SMA participation (Roland et al. 1980).

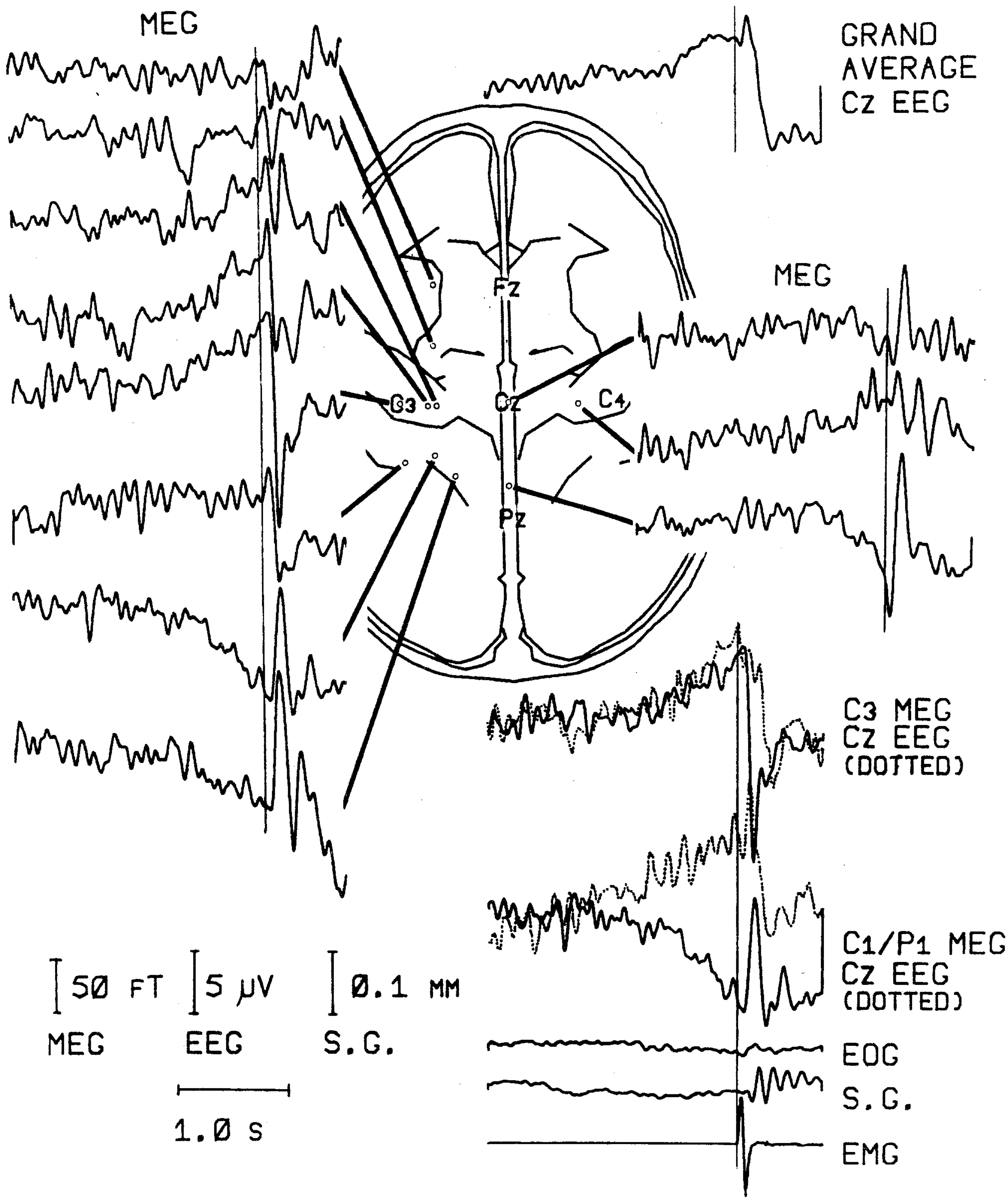


**Fig. 2.** Averaged MEG recordings over different locations on the scalp as indicated on the sketch showing upper cortical convolutions. Subject P.B. All averages are the result of successive blocks of 80 self-paced right finger flexions except for the grand average Cz EEG in the right upper corner. Vertical line indicates onset of electrical muscle activity (EMG). At the lower right is the MEG recorded over precentral (C3) and postcentral (C1/P1) locations with the simultaneous Cz EEG superimposed for comparison. Shown below are the EOG, head displacement (SG) and EMG for the postcentral average. Bandpass 0.03–15 Hz except for EMG (5–70 Hz). All recordings were done with breath holding

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