Evidence of a Nonlinear Human Magnetic Sense

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Abstract

Objective. First, to determine whether the onset of 2 G, 60 Hz induced transient potentials in the human brain, and to assess their duration, latency, and relation to stimulus onset. Second, to test the hypothesis that the potentials were nonlinearly related to presentation of the stimulus; this was accomplished by comparing the results obtained using nonlinear (recurrence analysis) and linear (time averaging) methods to detect the putative potentials.

Methods. Seventeen clinically normal subjects were studied: 8 males (age range 20–51 years) and 9 females (18–50 years).

Uniaxial magnetic fields, 2 G, 60 Hz, uniform to within 5% in the region of the head, were applied by means of two sets of three coaxial coils (Fig. 1a).

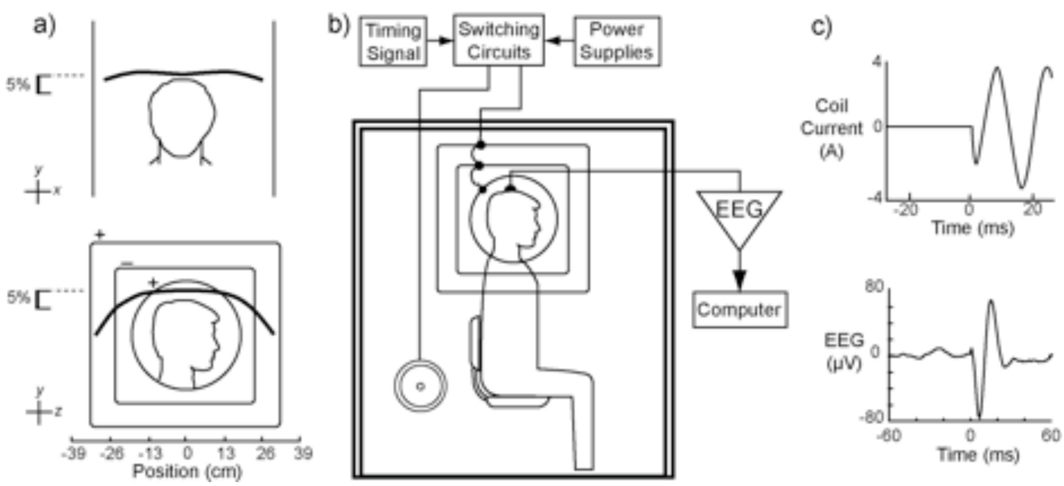


Fig. 1. a) Magnetic field generated by coils. b) Measuring circuits. c) Top, response of the coil current to instantaneous application of coil voltage. Bottom, curation of the induced spike in an O_1 electrode.

To detect potentials caused by onset of the field, the EMF was applied for 2 seconds and the EEG voltage signal, V(t), recorded after field onset (during the presence of the field) was analyzed; a portion of the signal recorded during the interstimulus period served as the control. The spikes in V(t) due to onset of the field were deleted by removing the first 30 ms (10 points, see below) after occurrence of the stimulus.

EEGs (O_1 and O_2, International 10–20 system) were amplified, filtered to pass 0.5–35 Hz, and sampled at 10 kHz. For analysis, the signal was divided into consecutive 7-second intervals (trials) (each consisting of field onset at t=0, field offset at t=2 seconds, and a 5-second inter-stimulus period). Artifact-free trials were sub-sampled at 300 Hz and digitally filtered between 0.5–35 Hz after removal of the spikes. All results were based on data from at least 50 trials.

For detection of evoked potentials by means of recurrence analysis, the epochs of interest in V(t) (t=0.03–1 s and 5.03–6 s, corresponding to onset and control intervals, respectively) were embedded in phase space, and recurrence plots for each of the epochs were generated and quantitated by means of percent recurrence, %R(t) (the nonlinear quantifier used to characterize the effect of the field). %R(t) was obtained as follows. The first 100 ms of each V(t) epoch were embedded in a 5-dimensional phase space using a time delay of 5, and the corresponding recurrence plot was generated (scale, 15%) and quantified using %R. The process was repeated using a sliding window of 1 point in V(t), yielding %R(t). That time series was smoothed (100 ms, step-1 averaging window) resulting in ***%R(t)***, which was used in the analyses for evoked potentials.

Linear analysis was performed by time averaging V(t).

Each subject underwent a block of trials where the magnetic field was applied and a block where the field was not applied (sham exposure).

On the basis of a discriminant analysis of the EEG from 3 subjects we found that the potentials could be observed within 209–354 ms in ***%R(t)***; the remaining 14 subjects were applied prospectively.

The values of ***%R(t)*** in the onset epochs between 209–354 ms (45 points that described the determinism in V(t) at 109–454 ms) were compared separately with the corresponding points in the control epochs using the paired T-test (comparison-wise significance level, $P<0.05$). The probability of observing ≥6 significant differences by chance at $P<0.05$ in 45 tests is 0.02386 (at most). We planned to conclude that a subject had exhibited an evoked potential if ≥6 tests were pair-wise significant at $P < 0.05$ in O_1 or O_2, or both. The family-wise error rate for our statistical hypothesis was 0.0472. We regarded the observed effect as nonlinear if it was detected in ***%R(t)*** but not in V(t).

Results. Field onset produced changes in the signals from the occipital electrodes that were detected by recurrence analysis but not by time averaging (Fig. 2). V(t) after field onset did not differ from the control, as determined by comparing the onset and control epochs point by point up to t=1 second following field onset, using the paired T-test (Fig. 2, first column). In contrast, when the determinism in the onset epochs was captured using ***%R(t)***, differences in the point-by-point comparisons between onset and control epochs were found (Fig. 2, second column); the differences occurred at 268&ndah;354 ms (27 points) and 232–344 ms (35 points) in O_1 and O_2, respectively ($P < 0.05$ for each pair-wise comparison in each interval). No difference in ***%R(t)*** for the sham-field-onset epochs was found (Fig. 2, third column).

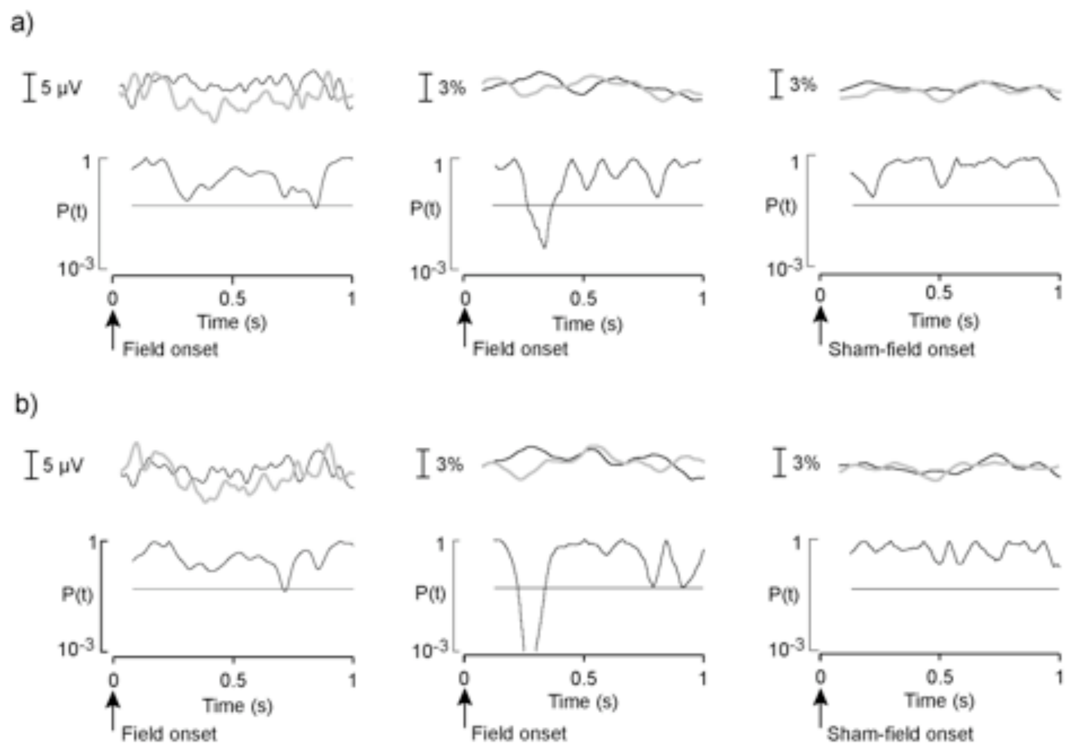


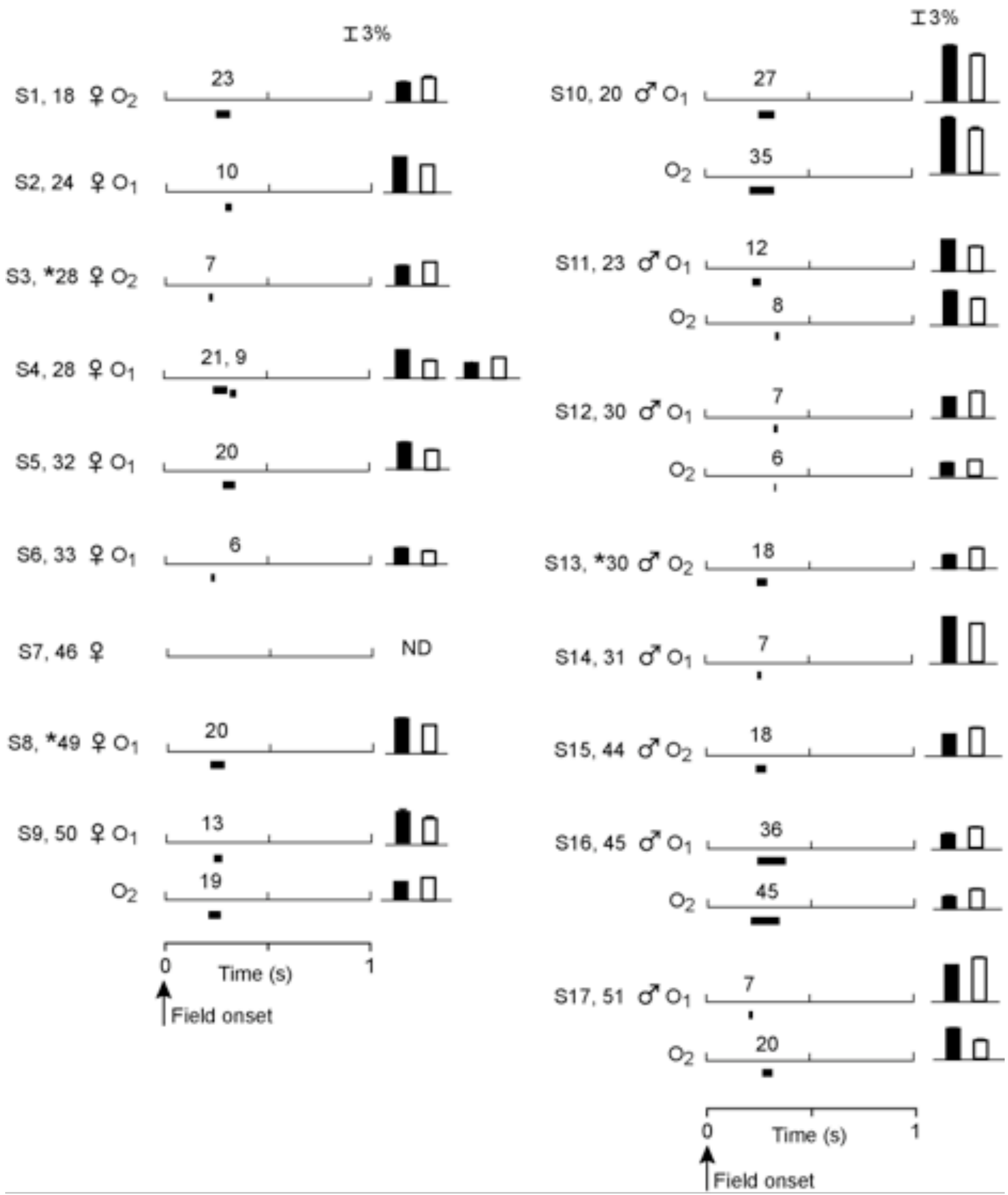
Fig. 2. Effect of onset of a magnetic field on brain electrical activity of a 20-year-old male. a), b), O_1, O_2, respectively. Solid line, P = 0.05. Onset (or sham-onset) and control epochs, black and gray curves, respectively.

Magnetosensory evoked potentials (MEPs) due to field onset were manifested in ***%R(t)*** from 16 of 17 subjects studied (Fig. 3). Latency and duration in each subject are indicated by a bar under the time axis. The number of significant points is shown above the axis. The bar graphs indicate the mean ± SD of the MEP observed in ***%R(t)*** (average of the significant points); black and white bars correspond to onset and control epochs, respectively (SD not resolved at scale presented). No false-positive effects were found in any of the 2 electrodes x 17 subjects = 34 sham-exposure analyses.

Using the method of time averaging, MEPs due to field onset were not detected in any electrode in any subject.

Discussion. We tested the hypothesis of a nonlinear magnetic sense in human subjects by examining the EEG for putative brain potentials evoked by onset of a magnetic field, using both linear and nonlinear methods of analysis.

Potentials due to field onset were detected in the occipital electrodes in 16 of 17 subjects (P < 0.05 in each of the 16 cases), using recurrence analysis (Fig. 3); no false positive effects were found using sham stimuli. All of the potentials occurred with a latency of 209–354 ms in ***%R(t)***(corresponding to 109–454 ms in V(t)), and consisted of statistically significant increases or decreases in ***%R(t)***, the quantifier used to capture the nonlinear determinism in V(t).



In conclusion, human subjects responded to onset of 2 G, 60 Hz, by exhibiting MEPs ($P < 0.05$ in each subject studied) at the occipital electrodes, with a latency of 109–454 ms. The potentials were nonlinearly related to the field.