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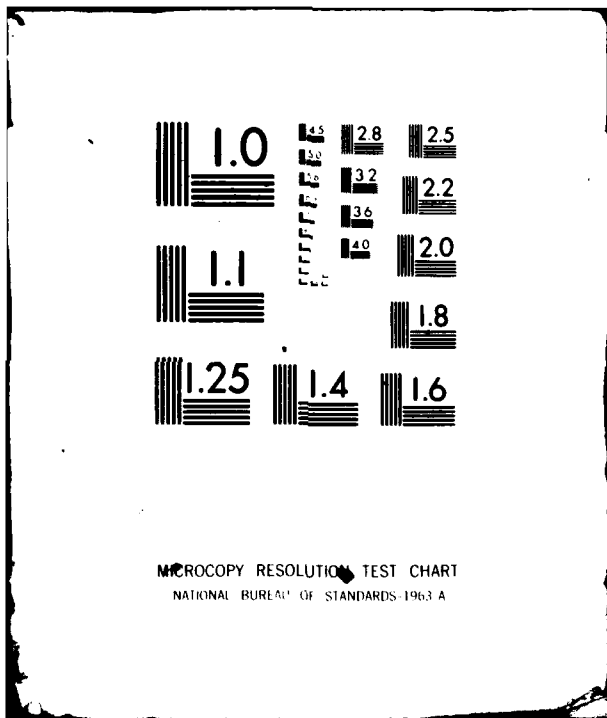
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APPLICATION OF A SQUID TO MEASUREMENT OF SOMATICALLY EVOKED  
FIELDS: TRANSIENT RESPONSES TO ELECTRICAL STIMULATION OF THE  
MEDIAN NERVE\*

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Introduction

In a previous investigation of somatic evoked fields (SEFs) (1), the little finger of one hand was stimulated by a periodic transcutaneous electrical stimulus to measure steady-state magnetic fields produced by cells in the primary projection area of the finger. The detectable fields normal to the skull were found to be well-localized within a small region of the somatosensory area, contralateral to the side of stimulation. Furthermore, the polarity of the fields was found to reverse when they were measured at different positions along the central fissure, suggesting that the current source of the SEFs can be localized within the somatosensory area. In a similar experiment carried out with the thumb, the iso-amplitude contours of the SEFs similar to that for the little finger were observed, but they were about 2 cm lower along the somatosensory area, in agreement with the classic map of somatotopic projection (2) in man. The above results showed that the evoked fields generated by a current source or sources can be measured and the source can be localized.

In the present study, the transient SEFs as opposed to steady-state SEFs were measured over the somatosensory area in order to study the time course of responses to stimulation of a somatosensory nerve and possible changes in polarity of the components of the transient SEFs over the somatosensory area. The shifts in polarity across the scalp should yield

information about the location of the current source(s) generating fields with varying latencies. Also, transient SEFs could be compared with somatic evoked potentials (SEPs) to examine the usefulness of SEFs and to see if the two types of data when considered together yield more insight about the nature of the underlying neural process.

The transient SEFs were obtained by electrically stimulating either the left or right median nerve and recording from either ipsilateral or contralateral hemisphere. The detection system consisted of a second-order gradiometer coupled to a superconducting quantum interference device (SQUID). The gradiometer is sufficiently well-balanced to reject uniform fields and fields with uniform gradients and to detect local spatial variations in the field in magnetically unshielded laboratory environments (3).

#### Method

**Stimulation:** A periodic 1.9 Hz train of electrical pulses, 1 msec in duration and 4 mA in amplitude, was generated by a Grass stimulator and applied to the left or to the right wrist with a pair of circular, brass electrodes (2.5 cm in diameter) placed at the base of the thumb and on the other side of the wrist. Stimulation of the median nerve was verified by the subject's reported sensation along the thumb and the first three fingers but not along the little finger of the stimulated hand. The current amplitude was near threshold for thumb twitch.

To measure the SEFs, the bottom, pick-up coil of the gradiometer was placed 1 cm away from the scalp with the axis of the gradiometer (2.3 cm in diameter) normal to the surface of the scalp. The SQUID output was amplified, applied to a comb-filter to reject 60 Hz and its harmonics, band-passed between 1 and 100 Hz and then was processed by a PDP 11/34

computer to recover the average transient SEFs.

Each session consisted of 2-minute long trials during each of which one median nerve was electrically stimulated while the subject lay still on a bed. He was given no extraneous task to perform. The data presented here are from one of four subjects. All were young male adults. Their results are essentially the same as those presented here.

### Results and Discussion

Transient SEFs recorded from the somatosensory region of the right hemisphere during the stimulation of the left wrist are shown in Fig. 1. Each record is an arithmetic average of responses to 480 stimulus pulses. The location of the pick-up coil for each record is shown in the right: The two numbers associated with each record represent the distances in cm above the auditory meatus and behind the nasion respectively. The path along which the pick-up coil was moved from one of its positions to the others was determined by first finding the locations at various heights from the ear canal that produced maximum responses as the pick-up coil was moved transversally. Transient SEFs along the transverse paths showed no obvious polarity reversals. The resulting track seems to run along the posterior side of the Rolandic fissure, according to its classic projection onto the skull (4).

The first notable feature is the orderliness of the data. As the pick-up coil was moved in small steps along the fissure, the waveform of transient SEFs changed gradually until the probe was near the null point 12 cm above the meatus and 16.5 cm posterior to the nasion, then its polarity reversed rather abruptly within a span of 2 cm, and as the pick-up coil was moved farther away from the null point the waveform again changed gradually, exhibiting a mirror-image symmetry about the null location. The data demonstrate that highly reliable

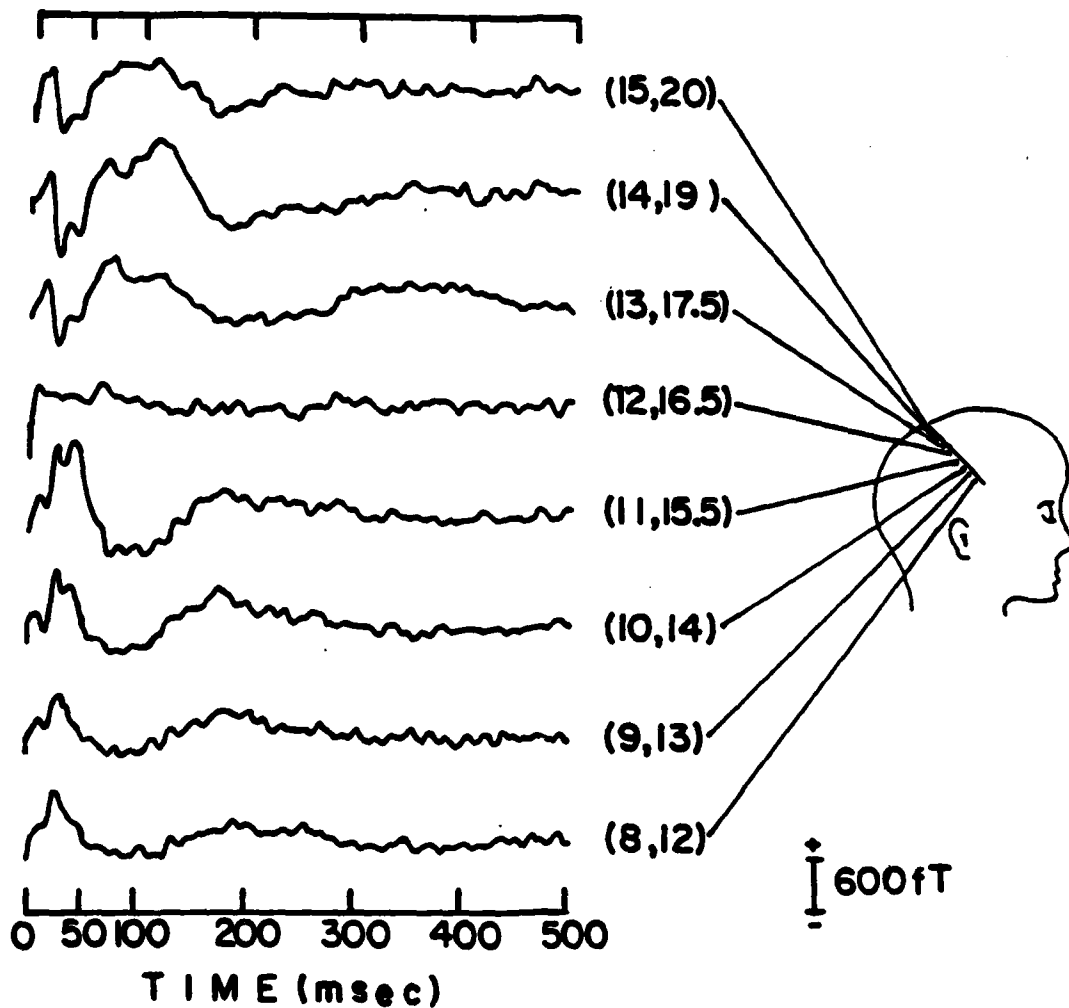


Fig. 1. The transient SEFs recorded from the right hemisphere of subject CS during the stimulation of the left median nerve. The pair of numbers at the right of each record indicate the position of the pick-up coil in the area above the right and back of the nasion.

transient SEFs can be measured with a second-order gradiometer.

The waveforms of the transient SEFs consist of several major components. The first has two small components with latencies

of 25 and 45 msec. Their latencies are highly reproducible across the various records in the figure and also across replications. The second major component has peak latencies between 75 and 125 msec. The peak latencies of the third component are between 175 and 250 msec.

The polarities of the major components reverse with longitudinal changes in the position of the pick-up coil, in agreement with the result described earlier for steady-state SEFs. The polarity of the first major component is positive below the null location and negative above it; thus, the fields with latencies between 25 and 45 msec emerge from the head below the null point and re-enter above. Similarly, it can be seen that the second component exits above the null point and returns below it, while the third component emerges from below the null point and returns at locations above. The polarity reversal of the major components at the same location suggests that they were all generated by a current source or sources located beneath the null location.

According to the classic map of somatotopic representation, the null point is located near the primary projection area of the median nerve (2). Thus, the current sources in the small region seem to have been isolated with the measurement of evoked fields.

The extent of SEFs seems to depend on size of the cortical projection of the somatosensory fibers. The amplitudes of the various components diminish noticeably over a distance of a few centimeters, but are more widespread than when the little finger was stimulated in the experiment described in the introduction. This discrepancy may be explained by the fact that in the present study the median nerve was stimulated at the wrist. Since the nerve innervates a large area of the hand and wrist, in addition to parts of the forearm, one would expect the fields generated in the cortex to be stronger and more widely spread over the somatosensory area

than the fields generated by stimulation of the branch of the ulnar nerve innervating the little finger. Thus, the transient SEFs in Fig. 1. may be thought of as due to multiple current sources in the cortex activated by various branches of the median nerve.

On the basis of the above characterization of the current sources, one would expect that the current sources in the two hemispheres to be symmetrically oriented and hence the polarity of the field from one hemisphere to be opposite that of the field from the other hemisphere. The transient SEFs from the left hemisphere of our subject, shown in Fig. 2b, demonstrate this expectation to be approximately correct. The records were obtained at locations between 8 and 17 cm above the left meatus with spacing of 1 cm. As in Fig. 1., the SEFs exhibit mirror symmetry about the null location which is a half centimeter above the corresponding null point in the right hemisphere (12.5 cm above the left meatus). But, the polarities of the major components are opposite in the two hemispheres at the homologous locations.

There are, however, some differences in the waveforms of the transient SEFs obtained from the two hemispheres. One salient difference is in the first major component, that is, in the complex occurring between 25 and 45 msec after stimulation. The component from the right hemisphere (Fig. 1) has two sharply defined peaks while that from the left hemisphere (Fig. 2b) has one prominent peak and another less obvious peak. The other major components also differ in their shapes somewhat across the hemispheres. The differences in the waveform might be due to differences in the amount of contribution of the multiple sources to the overall shape of the SEFs and suggest the possibility of uncovering the multiple sources with more analytical experimental procedures.

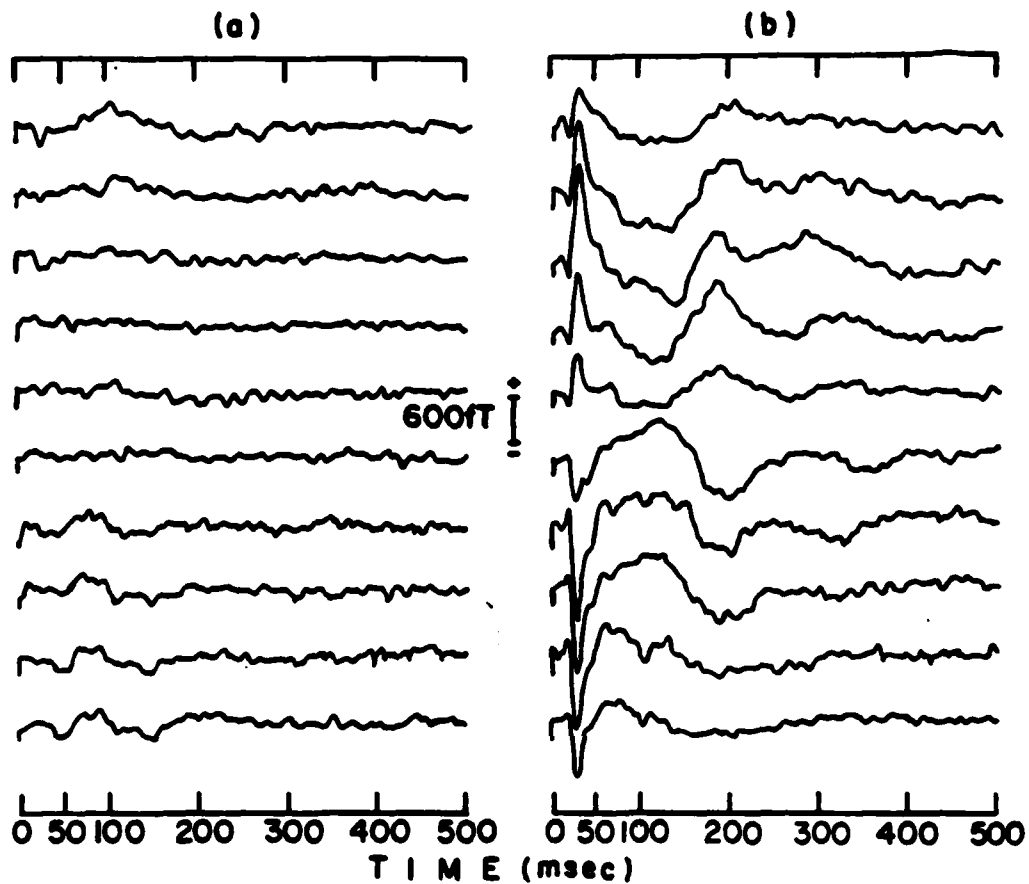


Fig. 2. The transient SEFs recorded from the left hemisphere of subject CS. (a) Responses obtained during the ipsilateral stimulation of the median nerve. (b) Responses obtained during the contralateral stimulation of the median nerve. The locations of the pick-up coil were between 8 and 17 cm spaced 1 cm apart.

The results so far have shown that the magnetic fields produced in a small region of the brain may be isolated and detected by the use of second-order gradiometers. The usefulness of the field measurement technique would be bolstered if it could reject magnetic fields produced by volume currents from far-away sources -- for example, volume currents

originating from the primary projection area of a median nerve on one side of the head spreading through the brain mass, the subdural fluids, the skull and the scalp. In order to see if such fields can be indeed rejected by the present field detection system, SEFs were measured from the left hemisphere while stimulating the left wrist. The locations of the probe were identical to those used with contralateral stimulation: SEFs were recorded at each of 11 locations by first stimulating the contralateral wrist and then stimulating the ipsilateral wrist.

The result is shown in Fig. 2a. Clearly, the ipsilateral response are near the noise level and are markedly different from the contralateral responses of Fig. 2b. However, one should note that a weak response was detected 17 cm above the meatus (the vertex is 18 cm above the meatus in this subject) and also a consistent pattern of ipsilateral responses between 8 and 11 cm above the meatus. The response at the higher position near the vertex is probably due to fields generated in the contralateral hemisphere as can be seen by comparing the polarity of the top record with the top record of Fig. 1. This spill-over is however quite small. The more interesting responses, perhaps, seen in the lower tracings of Fig. 2a are probably not due to volume currents because of the fact that some of the strong early contralateral components (e.g., the component with 25 msec latency) are not present and because of the limited region within which these responses are detected. Rather, these ipsilateral responses may be due either to signals traversing direct ipsilateral neural pathways or to transcollosal signals that activate neural tissue in the ipsilateral hemisphere. The SEFs recorded ipsilaterally then show that the fields generated by volume currents from the contralateral side of the head may be greatly attenuated.

Further insight into the nature of the source of the SEFs can be obtained by comparing it with recordings made with a small

electrode placed directly on the pial surface of the exposed brain of a human subject. Goff, Williamson, Van Gilder, Allison and Fisher (5) reported that the pial response reverses in polarity when the recording electrode was moved from the post- to the pre-central gyrus, but not when the electrode was moved parallel to the post-central gyrus. Their result is orthogonal to ours. Figure 3 shows SEFs recorded from

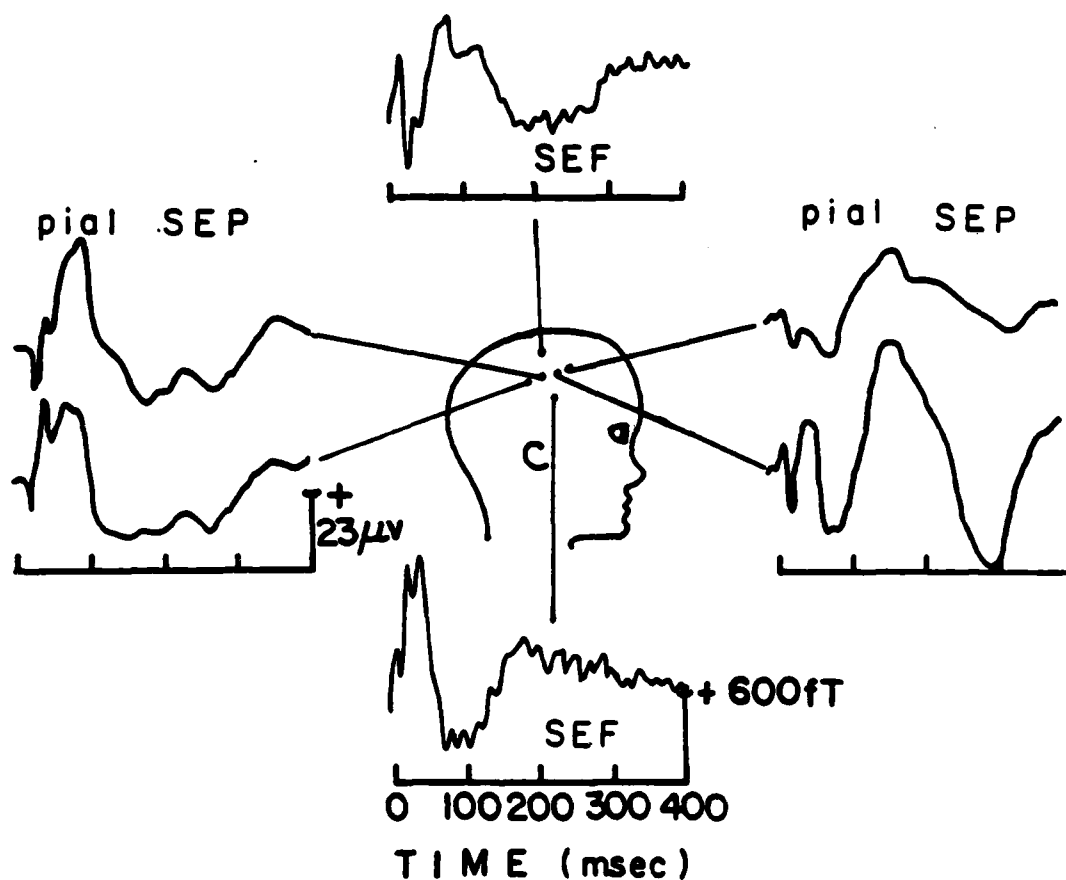


Fig. 3. A comparison of transient SEFs and pial SEPs. The transient SEFs were recorded from 11 and 13 cm above the right ear of subject CS; they are the same as in Fig. 1. The pial SEPs were recorded by Goff *et al.* (5) from the pre- and post-central gyrus near the primary projection area of the left median nerve.

locations 13 and 11 cm above the meatus on the right side of the head. These are the same records shown in Fig. 1. Also shown are pial SEPs recorded by Goff et al. (5). The SEPs were collected by stimulating the left median nerve with a train of 500 usec pulses, 3 mA above thumb-twitch threshold. The recordings were made from positions in the brain near where motor responses of the left hand, wrist and digits could be elicited by electrical stimulation. The conditions of sensory stimulation are comparable to ours since our lower stimulus intensity is offset by the longer pulse duration we employed.

The patterns of polarity reversals in the SEPs and the SEFs immediately suggest that both measures were produced by the same current source or sources. This idea can be examined by comparing the waveforms and polarities of the SEPs and SEFs. The SEPs recorded from the post-central gyrus contain three major components whose latencies are comparable to those of the SEFs. The first component has two peaks with latencies between 25 and 50 msec, the second has peak latencies of about 75 msec and the third has peak latencies between 150 and 250 msec. In the SEPs recorded from the pre-central gyrus, these components may be seen with their polarities reversed and in addition a fourth component with peak latencies of about 300 msec can be seen. This last component is either highly attenuated or is absent altogether in the SEFs. Thus, there is a remarkable similarity of the pial SEP and the SEF waveforms, even though some differences exist.

In addition to similarity of the waveform, the pattern of polarity reversals in the two types of measures strongly suggests that there is a large amount of commonality between the underlying sources for the SEF and pial SEP. The polarity of the first component of the pial recording shifts from + to - as the electrode is moved anteriorly across the central sulcus. This would mean that current is flowing from posterior to anterior. The corresponding component of the SEFs, on the

other hand, indicate that the fields emerge from the head below the null point and re-enter above the null point. This polarity reversal with longitudinal displacement of the probe is precisely what one would predict from the direction of current flow indicated by the pial recordings. The remaining correlated components of the pial SEP and the SEF are in the same relation to each other. Since the pial electrode senses extracellular current flow near the primary projection areas, the above comparison indicates that dense extracellular currents, such as the movement of ions in the intercellular space along apical dendrites of pyramidal cells, may be responsible for the SEF. In the light of its theoretical importance, this finding must be examined more closely, perhaps with animal models.

The results obtained in the present study have several theoretical and practical implications. The main result, demonstrating isolation and detection of the magnetic fields generated by a well-localized source or sources, implies that a small population of cells in the brain may be studied with the present non-invasive technique. The similarity of the SEF and the pial SEP furthermore implies that the cellular activity which can be studied with SEFs might be common to that revealed by evoked potentials recorded from the exposed surface of the human brain. The rejection of volume currents produced by far-away sources may be used to help localize the sources of various components of scalp-recorded SEPs and also evoked potentials obtained in other sense modalities. For example, part of the late components of the scalp-recorded SEPs with latencies greater than 100 msec might originate in the projection area of the nerve being stimulated, as Goff et al. (5) have identified using pial SEPs. This so-called somatic late response (SLR) is presumed by Goff and others to be ordinarily masked by the vertex potential in the scalp-recorded SEPs. The vertex potential, which probably is a composite of potentials produced by volume currents originating in

different parts of the brain, overlap in time with the SLR. Thus, it is difficult to isolate the two when the volume current smeared by the various media between the brain and the detecting electrode cannot be removed, as is the case with scalp-recorded SEPs. Since the SEF seems to circumvent the problem of diffused volume currents, it could complement the use of scalp-recorded SEPs.

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