Localization of human sensorimotor cortex during surgery by cortical surface recording of somatosensory evoked potentials

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The traditional means of localizing sensorimotor cortex during surgery is Penfield's procedure of mapping sensory and motor responses elicited by electrical stimulation of the cortical surface. This procedure can accurately localize sensorimotor cortex but is time-consuming and best carried out in awake, cooperative patients. An alternative localization procedure is presented that involves cortical surface recordings of somatosensory evoked potentials (SEP's), providing accurate and rapid localization in patients under either local or general anesthesia.

The morphology and amplitude of median nerve SEP's recorded from the cortical surface varied systematically as a function of spatial location relative to the sensorimotor hand representation area. These results were validated in 18 patients operated on under local anesthesia in whom the sensorimotor cortex was independently localized by electrical stimulation mapping; the two procedures were in agreement in all cases. Similar SEP results were demonstrated in an additional 27 patients operated on under general anesthesia without electrical stimulation mapping.

The following three spatial relationships between SEP's and the anatomy of the sensorimotor cortex permit rapid and accurate localization of the sensorimotor hand area: 1) SEP's with approximately mirror-image waveforms are recorded at electrode sites in the hand area on opposite sides of the central sulcus (P20-N10 precentrally and N20-P10 postcentrally); 2) the P25-N35 is recorded from the postcentral gyrus as well as a small region of the precentral gyrus in the immediate vicinity of the central sulcus: this waveform is largest on the postcentral gyrus about 1 cm medial to the focus of the 20- and 30-msec potentials; and 3) regardless of component identification, maximum SEP amplitudes are recorded from the hand representation area on the precentral and postcentral gyri.

KEY WORDS - cortical localization - sensorimotor cortex - evoked potentials

A HALF-CENTURY ago, Penfield and Boldrey reported their landmark study of motor and sensory representation in human cerebral cortex based on electrical stimulation of the cortical surface in patients undergoing resection of epileptogenic tissue. Many investigators had previously described motor responses to cortical stimulation in humans and animals, and Cushing had described sensations elicited by stimulation of the postcentral gyrus of an awake patient as early as 1909. However, it was Penfield and Boldrey's detailed summary of results in 126 patients that provided the foundation for practical localization of sensorimotor cortex in surgery. Accurate localization of sensorimotor cortex is necessary to minimize sensory or motor deficits when the area of intended resection lies in or adjacent to the sensorimotor region. Such localization is desirable for removal of tumors or other mass lesions, as well as resection of epileptogenic tissue.

Although mapping of sensory and motor responses elicited by cortical stimulation is undeniably useful as a means of localization, it has two disadvantages. First, stimulation of motor cortex sometimes elicits sensations and, conversely, stimulation of sensory cortex sometimes elicits movements. Without extensive and time-consuming mapping, the identity of the precentral and postcentral gyri may be ambiguous. Second, and
of more concern, effective use of stimulation mapping requires the use of local anesthesia. General anesthesia precludes the ability of the patient to report sensations and makes it difficult to elicit discrete movements. Adequate stimulation mapping thus requires an awake patient, which is difficult for the patient and surgical team alike. Moreover, it may be hazardous to open the cranium in awake patients with certain mass lesions, causing increased intracranial pressure.

Woolsey and his colleagues and others have also reported SEP's from the human cortical surface, but only Goldring and Gregorie have provided explicit guidelines for localization.

In this paper, we demonstrate that cortical surface SEP mapping during surgery provides a rapid and accurate means of localizing the hand representation area of sensorimotor cortex. First we describe the results of SEP mapping in a series of patients operated on under local anesthesia. Then we present recordings obtained in patients under general anesthesia to demonstrate that SEP mapping can be performed reliably under either type of anesthesia. Preliminary results have been published elsewhere.

Clinical Material and Methods

Cortical surface SEP recordings were made on 49 occasions from 46 patients; three patients required re-operation and were studied twice, with intervals ranging from 1 month to 4 years. The patients (16 females and 30 males) ranged in age from 4 to 71 years. Local anesthesia of the craniotomy margin, including analgesia and light sedation by Innovar (droperidol and fentanyl citrate), was used in 20 cases. General anesthesia, used in 29 cases, involved intubation under sodium pentothal followed by the delivery of 50% to 60% nitrous oxide in oxygen, often supplemented by Innovar and by 0.5% to 1.5% of a halogenated agent, typically isoflurane. The SEP's were recorded following craniotomy and reflection of the dura. A muscle relaxant was often administered prior to SEP recording, when the concentration of isoflurane or similar anesthetic was reduced. Following localization of the sensorimotor region, abnormal tissue was removed as follows: primary epileptogenic area in 18 cases; tumor in 25 cases; and other mass lesions in six cases.

Stimuli for SEP recording were 0.5-msec constant-current pulses delivered to the median nerve at the wrist at an intensity producing a moderate thumb twitch. Stimulus rates ranged from 0.4 to 2/sec and were either fixed or randomly varied over a range of 25% of the interval. Recording conditions have been improved since this study was begun in 1972. They originally involved the individual placement of eight to 16 silver ball electrodes in a "horseshoe" electrode holder.* This method has the advantage that electrodes can be placed individually and their locations accurately visualized. However, placement of the individual electrodes is time-consuming, particularly when multiple arrays are needed. Subsequently, we have used electrode arrays of various sizes and shapes embedded in a plastic sheet, similar to those described by Goldring.† The current configuration is a 64-electrode array consisting of an 8 x 8 grid (5 mm interelectrode distance) of silver balls 2 mm in diameter embedded in a sheet of 0.005-in. silicone rubber implant material.† This array can be placed rapidly but is not completely transparent and must be removed carefully after recording to correlate SEP results with the underlying pattern of sulci and gyri.

Cortical surface SEP's recorded from the sensorimotor region are large in amplitude (20 to 200 µV) and are relatively noise-free if electrocautery apparatus and similar devices are disconnected during recording; averages of 32 to 48 responses yielded highly repeatable recordings. Because the SEP's were so large and focal, various reference sites yielded equivalent results; we used either the ear, tip of the nose, or (with the 64-electrode array) a needle placed in muscle near the craniotomy margin, well away from the sensorimotor area. The electroencephalographic signals were amplified x 5000 to x 20,000, and filter settings were typically 1 to 1000 Hz (−3 dB) although a narrower bandwidth was occasionally used to minimize noise. The amplified signals were digitized in groups of eight to 32 channels at a rate of 2000 Hz.

Cortical stimulation to localize somatosensory and motor cortex (1 to 10 V, 0.5 msec duration, 50 Hz constant-voltage trains applied bipolarely with a tip separation of 5 mm) was carried out in all patients operated on under local anesthesia. The results were then used to guide placement of recording electrodes. In some patients undergoing surgery with general anesthesia we attempted cortical stimulation to localize motor cortex, but the time required and the difficulty in eliciting discrete movements led us to discontinue the procedure. In patients operated on under general anesthesia a visual estimate of the location of the sensorimotor hand area was made, electrodes were placed to span this region, and exploratory recordings were obtained. If necessary, additional recordings were made until adequate localization was obtained. The number of recording locations in a particular patient varied from 14 to 200 J. Neurosurg. / Volume 68 / January, 1988
Localization of human sensorimotor cortex

256; 32 to 128 locations were typical. Photographs of the exposed cortex alone and with the recording arrays in place allowed retrospective reconstruction of electrode locations with an estimated accuracy of 1 to 2 mm. In most cases, scalp recordings were also obtained before and/or after surgery.

Results

Localization Under Local Anesthesia

The morphology and amplitude of SEP's recorded from the cortical surface varied systematically as a function of spatial location relative to the sensorimotor hand representation. Figure 1 compares SEP's recorded from the postcentral (locations 1 to 5) and precentral (locations 6 to 9) gyri of the right hemisphere in a patient in whom the sensory and motor hand areas were identified by stimulation mapping. Stimulation (Fig. 1 [left]) at locations D and G elicited sensations of the fingers, whereas stimulation at locations C and E elicited hand or finger movements. Thus, locations D and G lie on the hand representation area of the postcentral gyrus, locations C and E lie on the hand area of the precentral gyrus, and the central sulcus lies under the large vein running between those two gyri. The SEP's were largest in the somatosensory and motor hand areas (Fig. 1 [right]) and were approximately mirror images in waveform across the central sulcus. At postcentral locations 2 and 3, SEP waveforms were negative-positive, whereas at precentral locations 7 and 8 they were positive-negative with similar peak latencies. Potentials with similar morphologies but smaller amplitudes were seen outside the hand area (postcentral locations 1 and 4, precentral locations 6 and 9).

![Figure 1](image-url)
Fig. 2. Somatosensory evoked potentials in relation to the anatomy of sensorimotor cortex and to the results of cortical stimulation. Upper Left: View of the left hemisphere of a patient (Case L13) under local anesthesia. Cortical stimulation: A, finger flexion; B, tingling of third finger; C, thumb tingling; D, speech arrest; E, face twitch; F, lip sensation; G, tingling in roof of mouth; I and J, paraphasia; and K, word-repetition deficit. CS = central sulcus; PoCS = postcentral sulcus; PrCS = precentral sulcus; and SS = sylvian sulcus. Upper Right: Two color topographic maps at the peak latencies of the 20- and 30-msec potentials (indicated by isolatency lines, lower). In this and subsequent topographic maps, tracings of the PrCS, CS, and PoCS are superimposed on maps from recordings using the 64-electrode array; each map therefore represents an area 35 x 35 mm. Positive voltage is indicated by the green and red end of the color scale, and negative voltage by the blue and purple end; each color represents 1/6 the voltage from minimum to maximum at the latency depicted. Electrode sites 43 and 46, located near the precentral and postcentral maxima, are labeled in the topographic map and the waveform plots in lower. Lower: Somatosensory evoked potential waveforms recorded from the 64-channel array. Isolatency lines are at the approximate peaks of the 20- and 30-msec potentials (23 and 36 msec, respectively).
FIG. 3. Somatosensory evoked potentials in relation to the anatomy of sensorimotor cortex and to the results of cortical stimulation. Left: View of the right hemisphere of a patient (Case V3) under local anesthesia. Cortical stimulation: A, arm flexion; B, wrist extension; C, wrist and elbow flexion; D, tingling in third and fourth fingers; E, tingling in first finger; F, mouth movement; and G, jaw movement. CS = central sulcus; PoCS = postcentral sulcus; PrCS = precentral sulcus; and SS = sylvian sulcus. Right: Somatosensory evoked potentials in response to stimulation of contralateral (solid lines) and ipsilateral (dotted lines) median nerves. Isolatency lines at the approximate peaks of the 20-, 25-, and 30-msec potentials are at 19, 23, and 29 msec, respectively.

ulation of the ipsilateral median nerve elicited no short-latency SEP activity (Fig. 1 right: dotted lines, locations 3 and 7); also see Figs. 3 and 4.

The SEPs with approximately mirror-image waveform across the central sulcus were observed in all patients except those in whom the hand area was not adequately exposed or in whom no SEP’s could be recorded (see below). We will refer to these postcentral and precentral waveforms as N2o-P30 and P20-N3o, respectively, corresponding to their polarity and average peak latency across subjects. However, as is evident in Fig. 1 and the following figures, the exact peak latencies of these SEP’s varied both between patients and between locations within a given patient.

The data just presented illustrate initial SEP recordings using the horseshoe array. Figure 2 illustrates SEP’s obtained using the 64-electrode array from the left hemisphere of a patient in whom stimulation mapping was also performed. The N20-P30 and P20-N30 waveforms (Fig. 2 lower) were obtained posterior and anterior to the central sulcus, respectively (Fig. 2 upper left). Both sets of potentials were largest in the somatosensory and motor hand areas on the postcentral (stimulation points B and C) and precentral (stimulation point A) gyri. This correspondence between the maxima and minima of the SEP distributions and the anatomy of sensorimotor cortex is best visualized in color topographic maps (Fig. 2 upper right), which illustrate SEP amplitude as a function of spatial position over the 64-electrode array using a color amplitude scale. Amplitudes at locations between recording electrodes were estimated by linear interpolation.

The N20-P30 and P20-N30 waveforms were seen in all patients in whom the entire sensorimotor region was exposed and in whom any SEP activity could be recorded. Thus, the polarity inversion of N20-P30 to P20-N30 across the central sulcus provides a first important criterion for localization of sensorimotor cortex. In addition, one or more positive peaks were often observed at latencies between the 20- and 30-msec activity. These intermediate potentials, which collectively will be termed P25 or P25-like activity, were more variable in appearance within and between patients. In some patients, P25 appeared as an additional intermediate peak on an otherwise typical N20-P30 waveform from the postcentral gyrus (Fig. 3). Stimulation mapping indicated that the somatosensory hand area in the patient depicted was near locations D and E (Fig. 3 left). Typical N20-P30 and P20-N30 waveforms were obtained from the postcentral and precentral gyri in this region (Fig. 3 right, locations 1 and 2). However, at more medial locations on the postcentral gyrus (location 3) a
distinct P25 peak was seen superimposed upon N20-P30.

In other patients, P25 was considerably larger than P20-N30 and was the dominant waveform in the medial region of the hand area (Fig. 4). In such cases, P25 was often followed by a negativity (N35). Typical N20-P30 waveforms are evident at postcentral locations 2, 3, and 4, and typical P20-N30 waveforms are seen at precentral locations 7, 8, and 9. However, at location 1, P25-N35 is seen in relative isolation. As in the preceding case, this P25 activity was largest somewhat medial to the largest 20- and 30-msec potentials (the P25 maximum was 9.9 ± 3.4 mm (mean ± standard deviation, SD) medial to the focus of the 20- and 30-msec potentials). Although P25 was largest just posterior to the central sulcus (location 1), it was also evident anterior to the sulcus (locations 5 to 7). Like N20-P30, the P25-N35 waveform was evoked by contralateral but not ipsilateral median nerve stimulation (Fig. 4, compare solid and dotted lines at location 1; also see Fig. 3, location 3).

Because of its focal distribution near the central sulcus, P25 provides a second important localizing criterion in addition to the approximate mirror-image relationship of N20-P30 and P20-N30 across the central sulcus. However, the presence of large (> 100 μV) positive-negative waveforms on the postcentral gyrus means that the central sulcus cannot be identified by using the polarity inversion criterion in isolation without regard to the relationships between SEP's and sulcal patterns. If the polarity inversion criterion alone were employed with the data in Fig. 4, one would conclude incorrectly that the central sulcus must lie between locations 1 and 2, especially since the peak latency of P25 was 24 msec, only slightly later than the N20 peak (22 msec). Thus, P25 provides useful localizing information but it can also complicate the identification of P20-N30. Additional examples of P25 and P25-like activity are shown below.

The results shown in Figs. 1 to 4 are representative of those obtained in the 18 patients in whom SEP localization was validated by independent localization by stimulation mapping. In no case was there a disagreement between the two localization procedures. The results of cortical stimulation were ambiguous in one case; only motor responses were obtained from two

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**Fig. 4.** Somatosensory evoked potentials in relation to the anatomy of sensorimotor cortex and to the results of cortical stimulation. Left: Diagram of the right hemisphere of a patient (Case E1) under local anesthesia. Cortical stimulation: A, throbbing of forearm and hand; B and C, forearm flexion and finger movement; D, flexion of hand and fingers; and E, tingling of third finger. PoCS = postcentral sulcus; CS = central sulcus; and PrCS = precentral sulcus. Right: Somatosensory evoked potentials in response to stimulation of the contralateral (solid lines) and ipsilateral (dotted lines) median nerve. Isolatency lines at the peaks of the 20-, 25-, and 30-msec potentials are at 22, 24, and 32 msec, respectively.

**Fig. 5.** Somatosensory evoked potentials (SEP's) recorded from sensorimotor cortex of the right hemisphere in a patient (Case P23) under general anesthesia. Left: Color topographic maps at the peak latencies of the 20-, 25-, and 30-msec potentials, corresponding to the isolatency lines at right. In this and subsequent topographic maps, numbers indicate the locations from which the waveforms depicted right were recorded. Right: The SEP waveforms at selected postcentral (1-3) and precentral (4-6) locations. Isolatency lines at the approximate peaks of the 20-, 25-, and 30-msec potentials are at 23, 26, and 31 msec, respectively.
Localization of human sensorimotor cortex

adjacent gyri, which by SEP recording were determined to be motor and somatosensory cortex.

Localization Under General Anesthesia

Having established that SEP recordings permit localization of the somatosensory and motor hand representation areas with an accuracy equivalent to that of stimulation mapping, we next investigated whether similar SEP patterns were evident under general anesthesia. Short-latency SEP's were always obtained when nitrous oxide at concentrations of 60% or less was used in general anesthesia. There was one exception, probably unrelated to anesthesia (see below). In some cases, SEP's were initially absent or small when 1.5% to 2.0% isoflurane or a similar anesthetic agent was used in conjunction with nitrous oxide. However, reliable potentials were recorded 10 to 15 minutes after the agent was discontinued or reduced in concentration to 0.5% to 1.0%.

Figures 5 and 6 show that N20-P30, P20-N30, and P25-N35 similar to those obtained under local anesthesia were all present with similar spatial distributions under general anesthesia. In Fig. 5 right, the N20-P30 waveform is seen at locations 1, 2, and adjacent areas of the posterolateral portion of the array. The P20-N30 waveform is seen at locations 5, 6, and adjacent areas of the anterior portion of the array. A large P25-N35 waveform is seen at location 3 and adjacent locations medial to the N20-P30 focus. Topographic maps (Fig. 5 left) indicate that the 20- and 30-msec distributions are dipolar in shape with extrema located on adjacent gyri as in recordings under local anesthesia (compare with Fig. 2). Only one distinct P25 peak is seen in this patient, with a spatial maximum location just posterior to and extending across the sulcus separating the 20- and 30-msec maxima. At some precentral locations (for example, location 4) both P20 and P25 are evident. Based on the similarity of these results to those obtained under local anesthesia (Figs. 1 to 4), we conclude that the N20-P30 maxima lie on the postcentral gyrus, the P20-N30 maxima lie on the precentral gyrus, and the sulcus running between them is the central sulcus (Fig. 5 left).

Figure 6 illustrates SEP's having a P25 and a spatially and temporally distinct later P25-like peak. The N30-P30 waveform is evident at locations 1 and 2, and P20-N30 is evident at location 6 (Fig. 6 right). These electrodes are near the spatial peaks of the 20- and 30-msec activity (Fig. 6 left), which lie on adjacent gyri separated by a clearly identifiable sulcus. At location 3, which is medial to the N30 focus and very near the sulcus, P25 is evident at 24 to 25 msec, 2 to 3 msec later than the N20 and P20 peaks. About 4 to 5 msec later another positive peak occurs which is largest at location 4, although it is also evident at locations 3 and 5.

In cases where complex waveforms prevent a clear separation of P20 and P25-like activity, amplitude distributions alone without regard to waveform morphology can be a useful criterion for localization. This relationship is evident in the waveform plot of Fig. 2 and is shown more quantitatively in Fig. 7, which presents topographic maps of root mean square voltage (a measure of total amplitude independent of waveform mor-

**Fig. 6.** Somatosensory evoked potentials (SEP's) recorded from sensorimotor cortex of the right hemisphere in a patient (Case D16) under general anesthesia. **Left:** Color topographic maps at the peak latencies of the 20-, 25-, and 30-msec potentials, corresponding to the isolatency lines at right. **Right:** The SEP waveforms at selected locations. Isolatency lines for the 20-, 25-, and 30-msec potentials are at 22, 24, 32 msec, respectively. The isolatency line for a later P25-like potential is at 29 msec.
C. C. Wood, et al.

Phylogeny) over the latency interval from 15 to 50 msec for each of four patients. In every case, the maximum amplitude focus is located on the postcentral gyrus near the central sulcus.

Geometric Relationships to Sensorimotor Cortex

The gross geometry of the central sulcus in the vicinity of the hand representation area has important implications for localization of sensorimotor cortex by SEP recording. The central sulcus in the hand area often forms a bend, as can be seen in Figs. 2, 3, and 5, and is shown more directly in Fig. 8 upper. Because of this bend, the hand area of the somatosensory cortex commonly forms a convex cap of tissue pointing toward the frontal midline. Hence an "on-axis" line passing through the maxima of the 20- and 30-msec distributions forms an acute angle (70° ± 12°, mean ± SD for 19 cases) with a line approximating the overall course of the central sulcus (the "CS line" in Fig. 8 upper).

These geometric relationships have two practical implications in surgery. First, it will be appreciated from Fig. 8 upper that a craniotomy margin passing through the hand area parallel to the midline may expose the postcentral N20-P30 focus but leave the more medial precentral P20-N30 focus or postcentral P25 focus unexposed. Three patients in this series had only the postcentral N20-P30 focus exposed. Second, a line of electrodes placed approximately perpendicular to the central sulcus but lateral to the hand area may record postcentral but not precentral waveforms (Fig. 8 lower). This could lead to the erroneous conclusion that the precentral gyrus was not exposed or that SEP's could not be recorded from it. Despite this knowledge, we often discovered retrospectively that the electrode array was not angled acutely enough with respect to the central sulcus line.

Localization with Incomplete Exposure of Sensorimotor Cortex

The results described thus far were obtained in patients whose craniotomies completely exposed the sensorimotor hand representation area. Useful localization information can also be obtained when the hand area is only partially exposed. The patient whose SEP's are depicted in Fig. 9 had a right parietal mass judged from computerized tomography scans to be near the somatosensory cortex. The SEP recordings from the initial 64-electrode array showed only postcentral waveforms; locations 1 to 8 are representative. A relatively large

Fig. 7. The topography of root mean square (RMS) amplitude over the 15- to 50-msec latency range in relation to the anatomy of sensorimotor cortex in four patients (Cases K2, D16, J22, and P22). The RMS values are positive and hence are in the green-red side of the color scale; each color represents 1/6 the total RMS voltage for a given patient. In each patient the right hemisphere was operated on under general anesthesia.

J. Neurosurg. / Volume 68 / January, 1988
Localization of human sensorimotor cortex

$N_{20}-P_{30}$ waveform was recorded from location 8, but in view of the large interpatient amplitude variability (see below) it was not clear whether this electrode was on the postcentral gyrus or posterior to it. A second array positioned under the anterior margin of the craniotomy revealed small but clear precentral waveforms at locations 9, 10, 13, and 14; all other locations in both arrays showed postcentral waveforms, largest at location 17. Thus, the location of the central sulcus was estimated as shown. The postcentral gyrus is usually less than 2 cm wide in the hand area; the sulcus indicated in Fig. 9 is therefore likely not the postcentral sulcus but one posterior to it. An astrocytoma was removed from the region shown with no demonstrable postoperative sensory loss.

Failure of Localization

In three patients it was not possible to record the SEP's despite probable exposure of the hand area and apparently adequate stimulating and recording conditions. The first patient, who had an astrocytoma involving the left sensorimotor cortex, showed no cortical...
FIG. 9. Localization with incomplete exposure of the hand representation area from the right hemisphere in a patient (Case H12) under general anesthesia. Stippling indicates the region of tumor excision following localization. The somatosensory evoked potentials (SEP’s) shown at right were obtained from two arrays, the second of which was placed anterior to the margin of the craniotomy (Cr). The central sulcus (CS) was not exposed but, from the SEP data, its trajectory was estimated as shown by the dashed line.

SEP’s in the scalp recordings in response to right median nerve stimulation before surgery. The second had a left frontal astrocytoma; no preoperative recordings were made. The third harbored a left parietal metastatic adenocarcinoma. Normal SEP’s were obtained in preoperative scalp recordings over the right hemisphere, but minimal SEP’s were evident over the left hemisphere. Cortical stimulation at moderate intensities showed that the lateral portion of the hand area was exposed, but no cortical surface SEP’s could be recorded. Cortical compression and edema were evident in all three patients; in two of the three, cortical stimulation elicited paroxysmal discharges in the sensorimotor hand area.

Discussion

The spatial relationships between cortical surface SEP’s and the anatomy of the sensorimotor cortex that form the basis of the SEP localization procedure are summarized schematically in Fig. 10. Three spatial relationships between the SEP’s and the anatomy of the sensorimotor cortex have proved useful in localizing the sensorimotor hand area: 1) P20-N30 and N20-P30 waveforms are recorded on opposite sides of the central sulcus and are maximal in the sensorimotor hand area. Aside from the exceptions noted above (inadequate exposure of the hand area or complete failure to record SEP’s), polarity inversion of the N20-P30 to P20-N30 waveforms across the central sulcus was a consistent feature of all recordings. A similar conclusion has been reached by others.6,17 2) The P25 and N35 waveforms are recorded from the postcentral gyrus as well as from a small region of the precentral gyrus in the immediate vicinity of the central sulcus; they are largest on the postcentral gyrus about 1 cm medial to the focus of the 20- and 30-msec potentials. Depending on their relative amplitudes and latencies, it may be difficult to distinguish postcentral P25-N35 from precentral P20-N30 (see Figs. 4 and 6). However, two features of the data permit accurate localization in spite of this ambiguity: a) negative-positive waveforms (N20-P30 or N20-P25-P30) were only observed posterior to the central sulcus and were largest on the postcentral gyrus; and b) the largest positive-negative waveforms (whether P20-N30 or P25-N35) invariably occurred in close proximity to the sulcus. 3) Regardless of specific waveform morphology and peak identification, the largest SEP amplitudes were recorded from the hand representation area on the precentral and postcentral gyri. Examination of raw waveforms (as in Fig. 2) or plots of overall amplitude (as in Fig. 7) allows localization of the postcentral gyrus as the one underneath the maximum amplitude focus.
Localization of human sensorimotor cortex

The following observations will aid the practical implementation of the SEP localization technique:

1. The zero-potential line dividing the postcentral and precentral parts of the 20- and 30-msec distributions lies very near the central sulcus on the major axis connecting the extrema of the two distributions (Figs. 2, 5, and 6). However, at locations away from the major axis of the distributions the zero potential line did not necessarily follow the contour of the central sulcus, since the orientation of the distribution depends upon the angle of the equivalent source in the region of active tissue and has no necessary relationship to cortical morphology outside the active region.

2. The N20-P30 and P20-N30 waveforms were largest on the precentral and postcentral gyri contralateral to the median nerve stimulated. In some patients, the region of large amplitude responses extended anteriorly and posteriorly onto adjacent gyri, but in no patient were large potentials recorded outside this region. No N30-P20, P35-N30, or P25-N35 waveforms were recorded in response to ipsilateral stimulation. Previous studies of cortical surface SEP's reached similar conclusions. These results strongly suggest that the potentials are generated in sensorimotor cortex itself. The specific cytoarchitectonic areas involved are discussed elsewhere (T Allison, G McCarthy, CC Wood, et al., in preparation). Suffice it to note here that we believe the 20- and 30-msec potentials are generated in area 3b of the somatosensory cortex, that P25-like activity is generated primarily in area 1 of somatosensory cortex and partly in area 4 of the motor cortex, and that cortical surface and scalp SEP's over much of the 20- to 40-msec range reflect the composite activity of these two generators. However, it is emphasized that the utility of hand area localization by SEP recording does not depend upon the validity of this or other hypotheses regarding SEP generators.

3. This technique uses a common reference electrode, typically a needle placed in temporal muscle adjacent to the craniotomy margin. Recordings from bipolar chains of electrodes have been used for localization of sensorimotor cortex. Goldring and Gregorie reported that a phase reversal of potential, reflecting an amplitude maxima, can be recorded consistently over somatosensory cortex but less consistently over motor cortex. In our experience, the precentral potentials can always be recorded (except in cases of complete absence of SEP's) provided that the precentral hand area is exposed. Figure 8 suggests that the less consistent precentral phase reversals reported by Goldring and Gregorie may result from placement of precentral electrodes lateral to the region of maximum P20-N30 amplitude, particularly since the bipolar chains were placed parallel to the midline. Bipolar recordings also sometimes yielded responses but no phase reversals, therefore necessitating localization by cortical stimulation. Similarly, King and Schell reported difficulties in distinguishing precentral from postcentral gyri using bipolar recordings. Such ambiguities do not occur with referential recordings.

4. Failure to record SEP's from the cortical surface occurred in three cases, presumably due to a combination of factors, including a tumor invading or abutting the sensorimotor cortex, cerebral edema, or the occurrence in surgery of spontaneous or evoked seizures.
involving the sensorimotor cortex (and perhaps producing a postictal depression). However, none of these conditions alone necessarily prevents the recording of SEP’s, since in other patients successful recordings were obtained despite the presence of each of these factors. Of the 42 patients from whom SEP’s were recorded preoperatively, the two who showed absent SEP’s over the affected hemisphere also showed absent SEP’s from the cortical surface (the other patient in whom intraoperative SEP recording failed was not studied preoperatively). Thus, failure to record scalp SEP’s preoperatively may be predictive of intraoperative failure as well. In such cases it may be possible to localize motor cortex by cortical stimulation. Of the two patients having no preoperative or intraoperative SEP’s, localization by cortical stimulation was successful in one but not the other.

5. Recording of SEP’s provides equally good localization under local or general anesthesia. Although they may be influenced by anesthetic agents, reliable short-latency SEP’s similar to those under local anesthesia are present under general anesthesia.1,8 Direct comparison with SEP’s recorded from the scalp is not possible in recordings made following a craniotomy. However, potentials recorded intraoperatively under local anesthesia were similar in waveform and topography to those obtained under general anesthesia, and either type of intraoperative SEP was similar to scalp recordings made preoperatively except for a slight (1- to 3-msec) increase in latency presumably due to sedative or anesthetic effects or to the effects of brain cooling.9 Somatosensory evoked potentials have been recorded from the cortical surface under anesthesia using nitrous oxide and up to 2% halothane.11,20 Circumstantial evidence in a few patients in our series suggests that high concentrations (1.5% or more) of enflurane or isoflurane in nitrous oxide can greatly reduce or abolish SEP’s. We currently reduce the concentration of these agents to 0.3% to 0.5% a few minutes before and during recordings. If necessary, a muscle relaxant is administered to prevent movement.

6. Successful hand area localization was obtained in patients from 4 to 71 years of age. Apart from small differences in absolute latency associated mainly with height, no systematic effects of age or sex were noted.

7. If the initial estimate of the location of the hand area is correct, total preparation and recording time using the 64-electrode array is about 15 minutes. If the initial estimate is incorrect (in this series it was incorrect about half the time) the array is moved and the procedure repeated until the hand area is localized. Each repetition requires an additional 5 to 10 minutes.

8. The total time required for localization obviously depends upon the number of channels that can be simultaneously recorded. We currently record simultaneously from 32 electrodes of the 64-electrode grid. However, adequate localization can be obtained with as few as four to eight electrodes. With a small number of channels, consideration of the geometric relation-

ships between the on-axis line and the CS line is particularly important (see Figs. 8 and 10). In such cases, our experience suggests the use of an initial mediolateral array to identify the region of maximal amplitude, followed by an anteroposterior array along the best estimate of the on-axis line to identify the precentral and postcentral gyri.

9. The guidelines for localization given above are based on relative SEP amplitudes as a function of spatial position in relation to the sensorimotor hand area. Absolute amplitudes, in contrast, are less generally useful because of large interpatient variability. Nevertheless, extremely large absolute amplitudes can provide a conservative criterion for localization. For example, in 20 patients with complete coverage of the sensorimotor region, the maximum peak-to-peak amplitude of N20-P30 on the postcentral gyrus ranged from 30 to 490 µV whereas the maximum amplitude of P20-N50 on the precentral gyrus ranged from 20 to 360 µV. Ten of the 20 patients had absolute amplitudes greater than 100 µV; in eight of these 10, amplitudes greater than 100 µV were confined to the precentral and postcentral gyri.

10. Two types of potentially helpful localizing information have not proved useful: a) The need for neurophysiological techniques of localization assumes that correct identification of the sensorimotor cortex cannot be made by visual inspection of the exposed cortical surface. We reinvestigated this question by reviewing in all patients the morphology of the sulci, gyri, and overlying vasculature. No consistent pattern was observed. While the central sulcus often makes a characteristic bend in the region of the hand area (see Figs. 2 and 8), it sometimes does not, and in any case similar bends were also seen in the precentral and postcentral sulci (see Fig. 8). In patients with large mass lesions and consequent displacement of tissue, or with edema and cortical compression, it was often impossible to see the sulci, much less attempt to identify them. We thus reaffirm that variability in the configuration of gyri and surface vasculature prevents their use for identification of sensorimotor cortex. b) Depending on the location of the craniotomy and proposed resection, it may be desirable to localize the sensorimotor face and leg areas instead of (or in addition to) the hand area. Morrell and colleagues14 noted that SEP recording allowed localization of the primary receiving areas of hand, leg, or face. Goldring and Gregorie15 stated that the face area could be identified by SEP recording using a light tap to the lip as the stimulus. However, neither group has as yet published extensive recordings of such activity. We have attempted to record SEP’s evoked by electrical stimulation of the lips (six cases) or of the posterior tibial or peroneal nerve (five cases). Reliable potentials were recorded in some cases, but their topographic relationship to the central sulcus (as determined by hand area recording and cortical stimulation) has not as yet been consistent enough to provide reliable localizing criteria.
Localization of human sensorimotor cortex

Conclusions

These results demonstrate that the spatial relationships between SEPs and the anatomy of the postcentral gyrus, precentral gyrus, and central sulcus provide an accurate and reliable basis for hand area localization that is equally effective under local and general anesthesia. Although the procedure should be useful in any situation requiring precise knowledge of the location of sensorimotor cortex, we have found it to be particularly valuable in the following clinical contexts. In cases where frontal or parietal neocortex is identified as the primary epileptogenic region in patients with intractable focal epilepsy, localization of the sensorimotor region by SEPs allows maximal resection of the focus without risking sensory or motor deficit. Similarly, SEP localization allows more complete resection of cortical regions invaded by tumors while minimizing sensorimotor deficit. The technique is particularly helpful when tumors or other space-occupying masses have distorted normal cortical anatomy. Finally, SEP localization is useful in children or other cases in which the use of local anesthesia should be avoided.11,12

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