ductor due to the foramen magnum (Lueders et al. 1983) seems unlikely, because the foramen magnum was removed by suboccipital craniectomy in our patients.

Since we failed to record reproducible far-field scalp potentials following lower limb stimulation, it could not be definitely concluded whether or not the N1′ component also coincided in latency with any of the far-field scalp potentials. However, the identical generation mechanism of N1′ to that of N1 as indicated by the present study would make it reasonable to assume that N1′ also contributes to scalp far-field potentials induced by PTN stimulation. This issue should be investigated in a future study.

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Origin and distribution of brain-stem somatosensory evoked potentials in humans

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Summary The distribution of somatosensory evoked potentials (SEPs) recorded from the brain-stem surface was studied to investigate their generator sources in 14 patients during surgical exploration of the posterior fossa. Two distinct SEPs of different morphologies and electrical orientation were obtained by median nerve stimulation. A small positive-large negative-late prolonged positive wave was recorded from the cuneate nucleus and its vicinity. There was a phase-reversal between the cuneate nucleus and the ventral surface of the medulla, depicting a dipole for dorso-ventral organization. From the pons and midbrain, triphasic waves with predominant negativity were obtained. This type of SEP had identical wave forms between the dorsal, lateral and ventral surface of the pons and midbrain. It showed an increase in negative peak latency as the recording sites moved rostrally, suggesting an ascending axial orientation. In a patient with pontine hemorrhage, the killed end potential, a large monophasic positive potential was obtained from the lesion. This potential occurs when an impulse approaches but never passes beyond the recording electrode. Therefore, the triphasic SEP from the pons and midbrain reflects an axonal potential generated in the medial lemniscal pathway.

Key words: Brain-stem; Cuneate nucleus; Killed end potentials; Medial lemniscus; Median nerve stimulation; Somatosensory evoked potentials (SEPs)

Although somatosensory evoked potentials (SEPs) obtained from the brain-stem have been studied during stereotaxic surgery (Larson and Sances 1968; Liberson et al. 1970; Strassburg et al. 1979; Colombo 1984; Hashimoto 1984; Katayama and Tsubokawa 1987; Morioka et al. 1989) and posterior fossa surgery (Lueders et al. 1983; Suzuki and Mayanagi 1984; Moller et al. 1986, 1990; Urasaki et al. 1990), their precise distribution and physiological significance remain unclear, due mainly to limitations in numbers of recording sites simultaneously studied. Most of the authors (Larson and Sances 1968; Liberson et al. 1970; Strassburg et al. 1979; Colombo 1984; Katayama and Tsubokawa 1987; Morioka et al. 1989) recorded SEPs only from the upper part of the midbrain or the rostral side of the medial lemniscus. Hashimoto (1984) and Urasaki et al. (1990) reported brain-stem SEPs recorded from different sites, however, they included recording sites from the 4th ventricle that were apart from the brain-stem.

We obtained a variety of SEPs from different sites of the brain-stem, using a small ball electrode, placed in open surgical conditions in direct contact with the pial surface of the brain-stem. Such an approach enabled us to search for the precise estimation of the distribution and generator sources of SEPs on the brain-stem surface.

Subjects and methods

Fourteen Japanese patients, 7 men and 7 women, who underwent posterior fossa surgery were the subjects of the present study. Thirteen of 14 patients had no intrinsic lesion in the brain-stem itself and showed normal scalp-recorded SEPs. There were 6 patients with cerebello-pontine angle tumor, 1 with hemifacial spasm, 1 with vermian tumor, 1 with cerebellar tumor, 1 with tumor at quadrigeminal plate, 1 with temporal lobe glioma, 1 with arteriovenous malformation in the middle cerebellar peduncle and 1 with vertebral aneurysm. The other patient had pontine hemorrhage with abnormal scalp-recorded SEPs. Their ages ranged from 12 to 67 years, with a mean of 45 years. The records were made in the course of routine intraoperative monitoring of SEPs. Informed consent was obtained from the patients and their families before the surgery.

Under general anesthesia, the patients underwent suboccipital craniectomy and the surface of the brain-stem was exposed. Anesthesia was of the nitrous oxide-

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fentanyl-droperidol type. Brain-stem SEPs were recorded with a sterile silver ball electrode (Unique Medical, KU 88-060), with a diameter of 1 mm and tip exposed for 0.5 mm in length. It was positioned on different sites of the dorsal, lateral and ventral surface of the brain-stem by the surgeon.

Either a cephalic or non-cephalic reference derivation was used to record SEPs. For the cephalic reference, silver-silver chloride disk electrodes were placed on Fz (10–20 international system). For the non-cephalic reference, the disk electrode was placed on Erb's point of the side opposite to stimulation. Impedances of the reference electrodes were kept below 3 k Ω. Electrical stimulation of the median nerve at the wrist was achieved with square wave pulses, 0.1 msec in duration and 4/sec in frequency. Stimulation intensity was adjusted to produce weak contractions of the thumb. SEPs were recorded by using a Cadwell Quantum 84 averager, with a bandpass filter setting between 10 and 3000 Hz (−3 dB) and averaging 100 responses with an analysis time of 30 msec. The recordings were repeated at least twice to ensure reproducibility of the response.

Recording of scalp SEPs was followed by guidelines of the American Electroencephalographic Society (1984). Disk electrodes were placed bilaterally on Erb's points, the cervical spine over the 5th process (Cv), Fz and somatosensory hand area on the scalp (C3' and C4'; 2 cm posterior to C3 and C4, respectively). A montage consisting of C3' or C4'-contralateral Erb's point, C3' or C4'-Fz, Cv-Fz and Erb's point-Fz was used for a 4-channel system. The recording and stimulation conditions were the same as those for brain-stem SEPs except that they were averaged over 500 times. In all studies a relative negativity at the exploring electrodes produced an upward deflection.

Results

(1) Records from the cuneate nucleus and its ventral side

The wave form of the response recorded from the ipsilateral cuneate nucleus was characterized by a large negativity with a peak latency of 13.2 msec, preceded by a small positive deflection, and followed by a large positivity with a peak latency of 20.3 msec (Fig. 1, upper trace). The wave form obtained from the ipsilateral pyramis (the ventral surface of the medulla) had a broad positivity with a peak latency of 13.2 msec, followed by a large negativity with a peak latency of 20.6 msec (Fig. 1, lower trace). The positivity and the subsequent negativity corresponded in latency to the negativity and the second positivity from the dorsal surface, respectively, suggesting that there is a phase-reversal between the cuneate nucleus and the pyramis. The amplitude of the response from the dorsal surface was larger than that from the ventral surface, suggesting

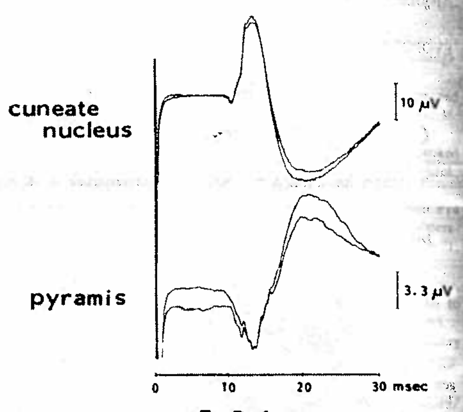

Fig. 1. Somatosensory evoked potentials (SEPs) recorded from the left cuneate nucleus and left pyramis in a 57-year-old woman with a left saccular vertebral aneurysm. The shape of the SEPs from the ipsilateral cuneate nucleus reveals a large negativity, preceded by an initial small positivity and followed by a prolonged positivity (upper trace). Response from the pyramis shows a large positive-prolonged negative diphasic configuration (lower trace). There is a clear phase-reversal between the dorsal and ventral surface of the medulla. Note the different calibration.

that their generator sources are closer to the cuneate nucleus.

(2) Records from the dorsal surface of the brain-stem

To clarify the rostrocaudal distribution of the brain-stem SEPs on the dorsal surface, recordings were made from the midline of the 4th ventricular floor in 2 patients. Wave form of SEPs recorded from the obex (medulla: at almost the same level as the cuneate nucleus) was similar to those on the cuneate nucleus, consisting of initial positivity, major negativity with a peak latency of 13.4 msec and a second positivity (Fig. 2C). The second positivity was slightly smaller than that of the cuneate nucleus.

SEPs recorded at the level of the facial colliculus (lower part of the pons) and the orifice of aqueduct (upper part of the pons) showed a positive-negative-positive triphasic wave with the negativity being a predominant component (Fig. 2B and A). The 2nd positivity was apparently smaller than that of medullary SEPs. Peak latencies of the predominant negativity showed slightly progressive increase with caudo-rostral direction (15.7 msec at the level of the facial colliculus and 16.5 msec at the orifice of aqueduct).

Interpeak latency of the negativity between the obex and the facial colliculus was longer than that between the facial colliculus and the orifice of aqueduct (2.5

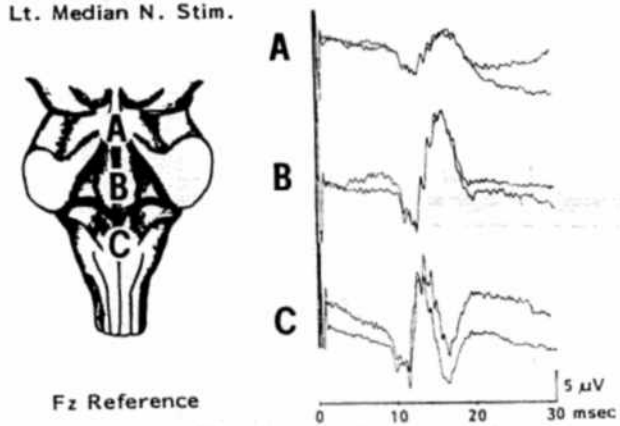

Fig. 2. Longitudinal distribution of SEPs recorded from the 4th ventricular floor in a 12-year-old boy with a vermian tumor. The recording sites are alphabetized on the schematic drawing of the brain-stem. From the medulla, an initial positive-polyphasic negative-large positive wave is obtained (C). The triphasic potentials recorded from the pons (B and A) have a smaller second positivity compared with that from the medulla. Note the conduction delay of the negativity between B and C.

msec versus 0.8 msec), though two interelectrode distances were the same. These findings suggested a conduction delay of the negative peak between medulla and pons.

SEPs, recorded at the level of the orifice of aqueduct in another patient, showed a triphasic configuration with a predominant negative peak latency of 15.6 msec (Fig. 5, right trace).

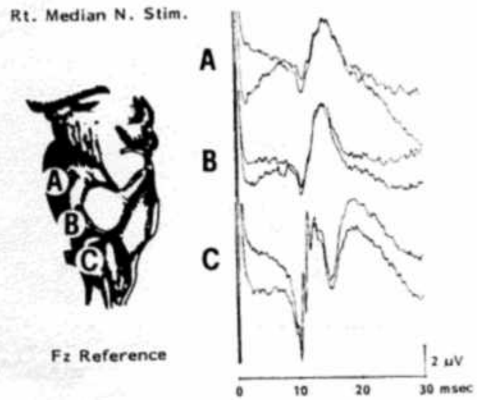

Fig. 3. Rostro-caudal distribution of SEPs, recorded from the lateral surface of the pons and medulla in a 36-year-old woman with a small acoustic neurinoma, illustrates almost the same as that obtained from the ventral surface.

(3) Records from the lateral surface of the brain-stem

Longitudinal distribution of SEPs on the lateral surface of the brain-stem, searched in 7 patients, showed similar to those of dorsal surface. On the medulla, a wave similar to those on the cuneate nucleus, initial positive-major negative (13.7 ± 1.1 msec in latency)-large second positivity, was obtained (Fig. 3C). From the lateral surface of the pons, a triphasic wave was recorded (Figs. 3A, B and 5, left trace). Negative peak latency at the root entry zone of the acoustic (lower part of the pons) and trigeminal nerve (middle part of the pons) was 14.1 ± 1.1 msec and 15.4 ± 1.3 msec, respectively. A conduction delay of the negative peak between medulla and pons was also seen.

(4) Records from the ventral surface of the pons

All potentials recorded from the midline of the ventral surface of the pons showed a triphasic wave with progressive increase in negative peak latency, as the recording was made more rostrally (Fig. 4). The negative peak latency of the response at the lower, middle and upper part of the pons is 15.1, 15.4 and 15.8 msec, respectively. This triphasic wave was not different in wave form from SEPs recorded from the dorsal and lateral surface of the pons.

(5) Records from the ventral and dorsal surface of the midbrain

SEPs obtained from the midbrain also showed a positive-negative-positive triphasic wave form which was similar to those from the pons. There was no difference

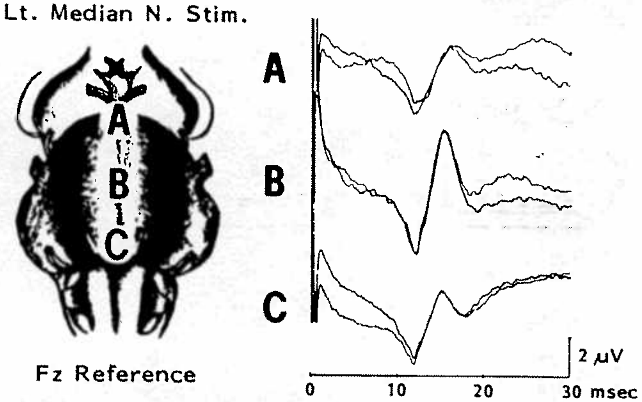

Fig. 4. Recordings from the ventral surface of pons in a 37-year-old woman with epidermoid in a right cerebello-pontine angle. Note the progressive increase in latencies of negativity as the recording site moves rostrally from C to B to A.

between the wave form of the quadrigeminal plate (dorsal surface) and the cerebral peduncle (ventral surface). Negative peak latency of the potentials from the quadrigeminal plate was 16.0 msec and that from the cerebral peduncle was 15.8 msec.

(6) Comparison of cephalic and non-cephalic reference derivations

Derivation with a non-cephalic reference yielded essentially identical SEPs to the cephalic reference derivation, in terms of wave form, onset and peak latencies, and amplitude of the major component. The non-cephalic derivation recorded short-latency components which was probably identical to P9 and P11 of the scalp far-field SEPs (Fig. 5, left trace). The 2nd positivity with a non-cephalic reference was smaller probably due to the effect of scalp widespread N16 or N18. However, 5 patients (33%) did not show short-latency components even with a non-cephalic reference derivation (Fig. 5, right trace).

(7) Records from a patient with pontine hemorrhage

This 29-year-old man with idiopathic pontine hemorrhage had normal scalp-recorded SEPs on right median nerve stimulation. On left stimulation there was no primary sensory cortical N20 component, though the cervical and far-field subcortical potentials were within

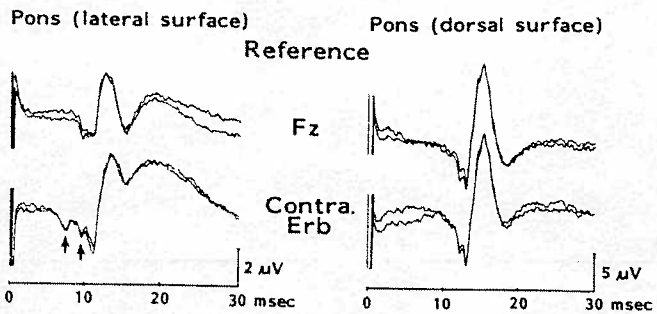

Fig. 5. Comparison of cephalic (upper traces) and non-cephalic reference (lower traces). The left traces, recorded in a 61-year-old woman with a right acoustic neurinoma, show short-latency components that precede the major negative component (arrows) when recorded with the non-cephalic reference. The right traces, recorded in a 33-year-old man with cerebellar hemangioblastoma, reveal no short-latency components irrespective of a non-cephalic reference. Abbreviations in this figure: Fz, midline frontal according to the international 10–20 system; Contra. Erb, contralateral Erb's point (supraclavicular point) to the stimulation.

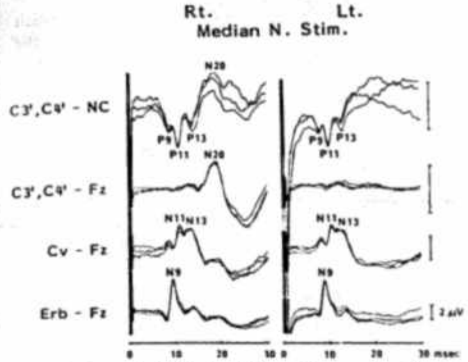

Fig. 6. Scalp-recorded SEPs in a 29-year-old man with idiopathic pontine hemorrhage. Note the normal SEP findings on right-side stimulation and absence of N20 on the left. Abbreviations in this figure: C3' and C4', 2 cm posterior to C3 and C4 (international 10–20 system), respectively. NC, non-cephalic portion such as the contralateral Erb's point with respect to stimulation; Fz, midline frontal; Cv, 5th cervical vertebra; Erb, Erb's point.

normal limits (Fig. 6). These findings indicated that the lesion disrupts the right medial lemniscal pathway.

Brain-stem SEPs were recorded from the midline of the 4th ventricular floor. Following right-side stimulation, a triphasic wave was obtained both from the caudal side of the hematoma and just from the hematoma (Fig. 7, left trace). Left stimulation evoked a positive-negative diphasic wave from the caudal side of the hematoma (Fig. 7B, right trace), and a monophasic positive wave was produced from the hematoma itself (Fig. 7A, right trace).

Discussion

(1) SEPs recorded from the medulla

The wave forms of the potential recorded from the cuneate nucleus are similar to those reported by previous studies (Andersen et al. 1964; Kaji et al. 1986; Møller et al. 1986, 1989, 1990; Jacobson and Tew 1988; Urasaki et al. 1990). Earlier animal studies by Andersen et al. (1964) indicated that the negativity of this potential reflects a synaptically induced depolarization of the cuneate cell produced by an ascending dorsal column volley. The subsequent positivity results from prolonged depolarization of synaptic terminals of fibers in the dorsal column tract. Recently Møller et al. (1986) demonstrated that the negativity is generated in the presynaptic termination of the dorsal column fibers and the positivity in the part of the postsynaptic potential of the cuneate nucleus. This is based on the evidence that the latency of the negativity had the same value as that recorded from the median nerve to the cuneate nucleus stimulation, and the positivity to orthodromic stimulation lasted much longer than to antidromic response. In our experience (Morioka et al. 1991), a higher rate of stimulation produced no measurable effects on the negative wave, while it markedly attenuated the positivity. Furthermore, the negative peak latencies on the cervico-medullary junction showed progressive increase with rostro-caudal direction, but the positive ones did

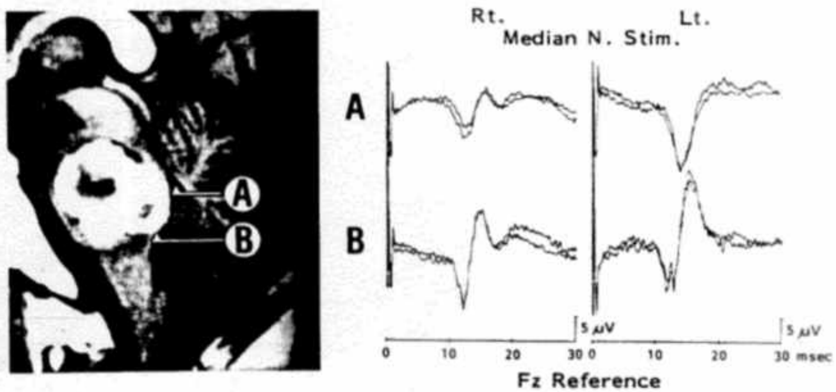

Fig. 7. SEPs recorded from the midline of the 4th ventricular floor in the same patient as the one described in Fig. 6. Recording sites are alphabetized on the sagittal view of the magnetic resonance image. A triphasic wave with predominant negativity is recorded following right median nerve stimulation (left trace). With left stimulation, a positive-negative diphasic wave is recorded from the caudal side of the hematoma (B, right trace) and the monophasic positive wave from the hematoma (A, right trace).

not. These findings are consistent with Møller's assumption.

Our observation that there is a phase-reversal between the cuneate nucleus and its ventral surface of the medulla indicates a dipole oriented in a dorso-ventral direction. Similar transverse dipole organization was observed in the lower cervical cord by Desmedt and Cheron (1981) using skin and esophageal leads, and by Jeanmonod et al. (1989) using a small silver ball electrode placed on the pial surface of the cord. Our finding provides the first evidence for a transverse dipole at the level of the medulla and is consistent with the anatomical finding that the dorsal column fibers project ventrally into the dorsal column nuclei (Willis and Coggeshall 1978).

SEPs recorded from the medulla were similar to those responses of the cuneate nucleus, though the second positivity was smaller than those of the cuneate nucleus. The second positivity was not so extended around the nucleus, probably because of the synaptic potentials. An analogous condition has been observed in our previous study of the thalamic SEPs (Morioka et al. 1989), in which the postsynaptic potential of the sensory relay nucleus is localized strictly to this nucleus and does not extend to any other nuclei.

(2) SEPs recorded from the pons and midbrain

Similar triphasic SEPs with predominant negativity have been observed from the ventral surface of the brain-stem (Suzuki and Mayanagi 1984) and from the 4th ventricle (Lueders et al. 1983; Hashimoto 1984; Urasaki et al. 1990). With respect to the generator sources of this major negativity, Hashimoto (1984) postulated that synaptic excitation within the pons and midbrain were progressively activated by an incoming volley from the ascending lemniscal system. Our study revealed that the triphasic wave was recorded from any surface of the pons and midbrain. An identical wave form recorded from any surface suggests that this potential has an axial orientation. The progressive increase in major negative peak latency from the more rostral site of the brain-stem indicates that ascending traveling waves were recorded. It is well known that a compound action potential of a nerve trunk placed in a conductive medium assumes a triphasic configuration (Willis and Grossman 1981), corresponding to the afferent volley approaching (positive), then passing underneath the electrode (negative), and eventually propagating beyond (positive). It was demonstrated that SEPs recorded from the most rostral part of the medial lemniscus have quite a similar potential with respect to wave form and latency (Morioka et al. 1989). Therefore, the triphasic SEPs recorded from the pons and midbrain reflect that the axonal potentials generated in the medial lemniscal pathway.

In our study, a conduction delay of the negativity was observed between the medulla and pons, which might be explained by the synaptic transmission of the cuneate nucleus. The interpeak latency between these two negativities probably reflects the synaptic transmission time and the conduction time from the nucleus to the pontine medial lemniscus after crossing the midline in the medial lemniscal decussation. The amount of delay is in the order of 1 msec, corresponding to the synaptic delay.

(3) Pathological wave form of brain-stem SEPs

In our case with pontine hemorrhage, on right median nerve stimulation, SEPs recorded from the dorsal surface of the pons showed a normal triphasic wave. However, on left median nerve stimulation, the previous triphasic response was abolished and in its place a positive monophasic potential was found. This wave could be identical to the 'killed end potential' reported by Woodbury (1965) and Deecke and Tator (1973). This kind of potential occurs when an impulse approaches, but does not arrive at the recording electrode, because the fibers terminate before reaching the electrode. The response is positive because the recording electrode in volume 'looks' at a huge sink as opposed to the source that never reaches the electrode (Woodbury 1965). Loss of the terminal positive phase on the caudal side of the hematoma may indicate that the ascending volley does not travel beyond the recording electrode and into the hematoma itself. Although extensive investigation of this killed end potential was made on the spinal cord potential (Schramm et al. 1983a, b; Whittle et al. 1986; Katayama et al. 1988; Makachinas et al. 1988), there seems to be no documentation on brain-stem potentials. This interpretation supports our assumption that brain-stem SEPs with a triphasic configuration are generated in the axonal potential of medial lemniscal fibers.

Also under pathological conditions at the cervico-medullary junction, the major negativity is replaced by the killed end potential (Morioka et al. 1990), which is consistent with our interpretation that the negativity of the cervico-medullary potential is of a presynaptic axonal origin.

(4) Far-field potentials on the brain-stem

Several authors (Hashimoto 1984; Suzuki and Mayanagi 1984; Katayama and Tsubokawa 1987) have described short-latency components that preceded the major component of the brain-stem SEPs, with identical peak latencies to the scalp-recorded far-field SEPs. We have confirmed this observation using both cephalic and non-cephalic references. However, 33% of the patients did not show short-latency components. This may be due to the change of volume conductor at the time of recording, such as suction of the cerebrospinal fluid or removal of the mass lesion.

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