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# DISTRIBUTION OF AUDITORY BRAINSTEM POTENTIALS OVER THE SCALP AND NASOPHARYNX IN HUMANS\*

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## INTRODUCTION

A dominant characteristic of scalp-recorded auditory brainstem potentials or responses (ABR) is their relative invariance over much of the surface of the human head, a fact accounted for by the "far-field" nature of the recordings.<sup>1</sup> A number of idiosyncracies in the scalp distributions of the various peaks have been noted, which may be relevant both for understanding the neural generators of these events and for defining recording arrays for clinical use.

Picton *et al.*<sup>2</sup> utilized a noncephalic reference and reported that wave I was largely restricted to the region of the mastoid and that waves I and III varied in polarity according to whether they were recorded from the mastoid ipsilateral or contralateral to a monaural stimulus. Waves I and III were negative in polarity for ipsilateral stimulation and positive in polarity for contralateral stimulation. Wave III, moreover, could be attributed to a theoretical source having both horizontal and vertical dipole components. Waves IV and V had positive polarities at all scalp locations and, while largest at the vertex, showed very little variation in amplitude over their electrode array.

Terkildsen *et al.*<sup>3</sup> also used a noncephalic reference and noted similar results. Wave I appeared as a negative deflection at the ipsilateral mastoid and as a positive deflection at the vertex. Waves II and III were a "single wave" at the ipsilateral mastoid and all subsequent peaks recorded from the vertex and mastoid were in phase.

Streletz *et al.*<sup>4</sup> reported that wave V recorded with a noncephalic reference was widely distributed over the scalp, but most prominent at the vertex. They also noted that, while wave I was recorded as a small positive potential at the vertex, it appeared as a larger negative potential at the mastoid ipsilateral to stimulation.

Stockard *et al.*<sup>5</sup> utilized an ankle reference and found that wave I was a negative deflection at the ipsilateral earlobe. Waves IV and V were positive at the earlobe. In a further comparison of waveforms obtained with referential recording between the vertex and ipsilateral and contralateral ears, both Stockard *et al.*<sup>5</sup> and Hixson and Mosko<sup>6</sup> confirmed earlier observations<sup>7</sup> that waves I and III are attenuated with a contralateral reference. Both studies defined that wave V was clearer using a contralateral rather than an ipsilateral earlobe as reference.

Van Olphen *et al.*,<sup>8</sup> however, reported no significant differences between the responses to ipsilateral and contralateral stimulation using the laryngeal prominence as a reference site, although no quantitative data were presented. In contrast to the previous studies, van Olphen *et al.*<sup>8</sup> also studied the anterior-posterior gradient of the ABR along the midline. While the maximum amplitudes were obtained at the vertex,

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sizable potentials were obtained as far anteriorly as the nasion, whereas at the inion all peaks were extremely small.

A map by Martin and Moore<sup>9</sup> of the ABR scalp distribution in humans is difficult to relate to the other studies because of the use of binaural stimuli. No asymmetries or polarity inversions were observed.

Thus, the various peaks of the ABR waveform differ in their relative amplitudes over the scalp, and some studies find that a few of the peaks have amplitude asymmetries in the lateral plane according to the ear of stimulation. In the present study we have made a systematic analysis of the amplitude distributions of all ABR peaks in both the lateral (coronal) and anterior-posterior (sagittal) scalp distributions using a noncephalic reference. A second purpose of the present experiments was to measure component latencies at several different electrode positions.

The definition of latency of the ABR components as a function of scalp derivation was not systematically investigated in these prior studies. Results from several animal species<sup>11,12</sup> have demonstrated that the latency of the ABR components do change across the scalp.

A third purpose was to study the ABR recorded from the human nasopharynx as reported by Martin and Coats.<sup>10</sup> They reasoned that nasopharyngeal electrodes might afford a unique view of the ABR since the electrode tip would be in close proximity to the presumed generators of the ABR and ideally positioned to distinguish lateralized differences according to the ear stimulated. They reported large differences in the amplitudes of two components, labeled NP3 (latency, about 4 msec) and NP6 (latency, about 7.5 msec), according to whether the stimulus was ipsilateral or contralateral to the nasopharyngeal electrode. They suggested that the NP3 potential may reflect near-field activity in the medial superior olive. In their study, however, the reference electrode was situated at the mid-forehead, which is now known to be an "active" site<sup>8</sup> and thus, the results do not allow for the definite separation of near-field potentials. In the study to be reported below, the nasopharyngeal electrode was referenced to a noncephalic site.

Finally, we compared the ABR derived from several recording arrays ( $C_z$  referenced to a noncephalic site,  $C_z$  referenced to either mastoid, and intermastoid recordings) to clarify the advantages and limitations of these various recording montages.

## METHODS

Eleven subjects participated in the study. All were laboratory personnel between the ages of 21 and 35 years. Their audiograms were not defined and hearing was assumed to be normal based on their own evaluation and their normal thresholds to the click signals.

Measurement of the amplitude of the ABR was made on five of the subjects, all male. Silver cup electrodes were applied to scalp with collodion at nine locations. A mid-sagittal array was formed by electrodes at the nasion (N), vertex ( $C_z$ ), inion (I), a frontal location (F) midway between the nasion and vertex, and a parietal location (P) midway between the vertex and inion. A coronal array was formed by electrodes at each mastoid ( $M_1$  and  $M_2$ ), vertex ( $C_z$ ), and at points midway between the vertex and each mastoid ( $L_1$  and  $L_2$ ). A noncephalic reference electrode was fastened to the skin over the seventh cervical vertebra ( $C_{VII}$ ) and a ground electrode was placed on the forearm.

The EEG was amplified 50,000 times with a bandpass of 0.35–10 kHz and

recorded on FM tape (bandpass, 0 to 5 kHz) for later analysis. The final bandpass during analysis was 0.1–3 kHz.

During testing, the subject was supine in a sound-attenuating chamber. Monaural condensation clicks generated by activating TDH39 earphones with 0.1 msec pulses were presented at 10/sec rate and at an intensity of 65 dB above the sensory level (SL). The five electrodes making up the sagittal or coronal array were recorded simultaneously. The  $C_z$  electrode was included in both arrays. Each ear was tested separately and replicate ABR waveforms averaged over 4096 trials were collected in a balanced order. The waveforms were displayed and amplitude measured from baseline (determined as the average value of the potential in a 3 msec period prior to stimulus presentation) to the peak of the wave. The latency at which each peak's amplitude was measured was derived from the ABR recorded at  $C_z$  for each subject.

To facilitate presentation of the coronal-array data, the electrode positions are labeled according to their relationship to the stimulated ear. Thus, the ABRs recorded from  $M_1$  and  $L_1$  for left-ear stimulation and  $M_2$  and  $L_2$  for right-ear stimulation are labeled  $M_1$  and  $L_1$  (ipsilateral), whereas the recordings from  $M_1$  and  $L_1$  for right-ear stimulation and  $M_2$  and  $L_2$  for left-ear stimulation are labeled  $M_c$  and  $L_c$  (contralateral).

In a second study latency measures of the ABR were made on six different subjects (three men, three women). Electrodes were affixed at  $C_z$ ,  $M_1$  (mastoid ipsilateral to stimulus),  $M_c$  (mastoid contralateral to stimulus), and referenced to  $C_{VII}$ . A nasopharyngeal electrode was inserted in each subject and also referenced to  $C_{VII}$ . Monaural condensation clicks were presented at 11/sec and at 65 dBSL to each ear and two sets of 2000 trials were collected to obtain duplicate averages. Appropriate manipulation of this data in computer memory allowed the definition of potentials between  $C_z$ – $M_1$ ,  $C_z$ – $M_c$ , and  $M_c$ – $M_1$ . (For instance, to obtain the  $C_z$ – $M_1$  derivation, the potentials recorded between  $M_1$ – $C_{VII}$  were subtracted from the potentials recorded between  $C_z$ – $C_{VII}$ .) Measures of polarity, latency, and amplitude of the various components were obtained from both the noncephalic referential recordings and the derived bipolar recordings.

## RESULTS

### *The Amplitude of Auditory Brainstem Responses*

The ABR waveforms over the scalp for one subject are shown in FIGURE 1. The grand-average ABR waveforms over two replications (8192 trials) for the right and left ears are superimposed. No significant amplitude differences were found as a function of whether the left or right ear was stimulated when the electrode sites were identified according to their relationship (ipsilateral or contralateral) to the ear stimulated. Six characteristic vertex-positive waves, labeled I–VI and five vertex-negative, waves labeled  $I_n$  to  $V_n$ , were identifiable at most electrode sites.

The mean amplitude of each peak are presented in FIGURE 2A. Wave I was positive in polarity at  $C_z$  and over the scalp contralateral to the stimulated ear. At the ipsilateral mastoid, the polarity of wave I was negative (FIGURES 1 & 3). The difference between the amplitudes of wave I at the ipsilateral and contralateral mastoids was significant at the 0.05 level. Waves  $I_n$ , II, IV, and V were largest at  $C_z$ , and were not significantly lateralized. Wave III was significantly larger at the contralateral mastoid and of opposite polarity than at the ipsilateral mastoid ( $p < 0.01$ ). Waves  $II_n$ ,  $III_n$ , and  $IV_n$  showed little amplitude variation across the array.

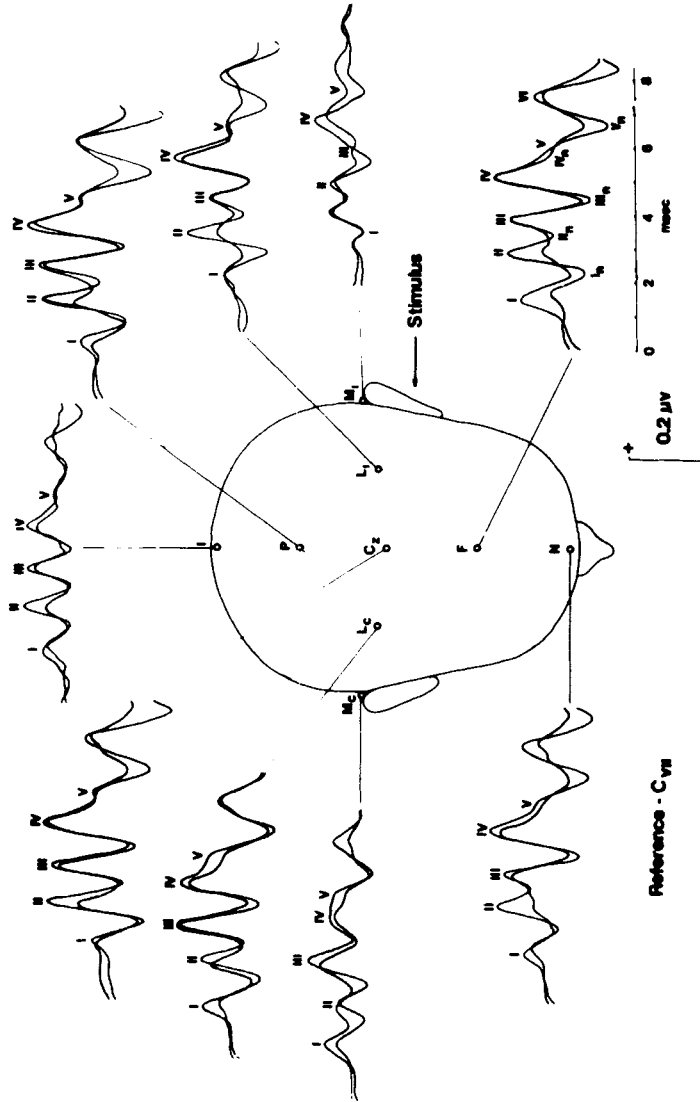


FIGURE 1. Auditory brainstem responses (ABRs) recorded from scalp electrodes in coronal and sagittal arrays referenced to a noncephalic site (seventh cervical vertebra,  $C_{VII}$ ). The stimuli were monaural condensation clicks, 65 dBSL, presented at a rate of 10/sec. Duplicate averages of 4096 trials are presented. The designation of I and C in this and all subsequent figures refers to the electrode site as being ipsilateral (I) or contralateral (C) to the ear being stimulated (designated by arrow).

Wave VI was generally negative with respect to the prestimulus baseline and showed no significant amplitude variation. There was, however, an overall tendency to more negative voltages over the contralateral scalp for the latter portion (6 msec and later) of the ABR waveform. This can be seen as a trend in the graphs for waves  $V_n$  and  $VI_n$ , and as a significant difference between the voltages at the two mastoids for wave  $VI_n$  ( $p < 0.05$ ) with the component being larger at the contra- versus ipsilateral mastoid.

The mean amplitudes for the sagittal array are shown in FIGURE 2B. The interpretation of amplitude of the ABR peaks in the sagittal distribution must be evaluated cautiously since the electrodes at the ends of the array vary in their

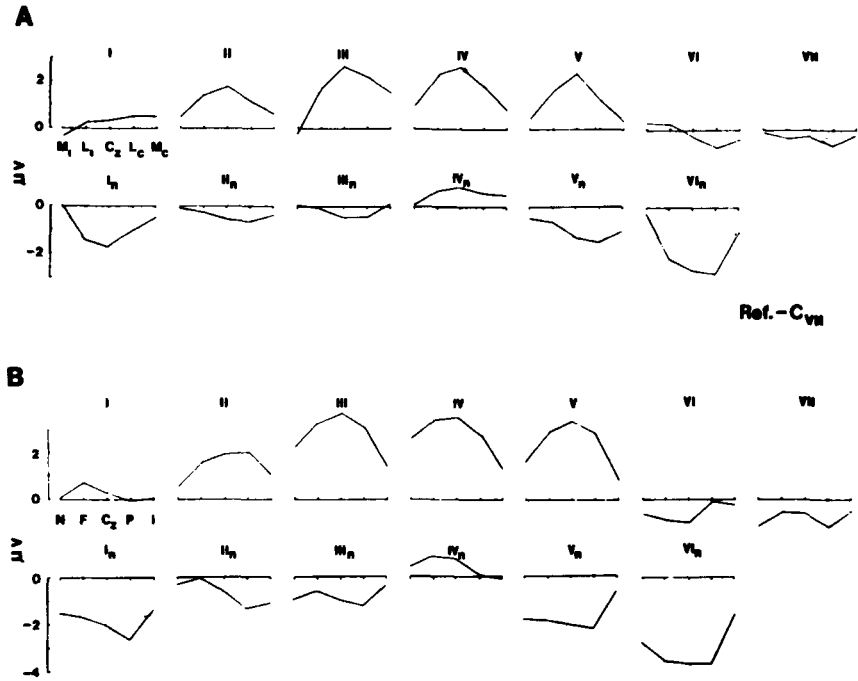


FIGURE 2. Amplitudes of auditory brainstem response components from different scalp locations. The data from the coronal array is in (A) and from the sagittal array is in (B). The amplitude scale is in tenths of microvolts.

longitudinal proximity to the reference electrode at the neck ( $C_{VII}$ ). While the reference electrode ( $C_{VII}$ ) was relatively inactive with respect to defining the ABR when recorded against an electrode even more remote from the scalp (first lumbar spinous process), it cannot be considered absolutely "referential" in recording the far-field reflections of the ABR. These considerations were not raised for the coronal array since the primary issue was the amplitude variation between electrodes equidistant from the "reference." Two general observations seem justified from the data of the sagittal array: first, wave I was largest over the fronto-central scalp, and decreased in amplitude posteriorly. For four of the subjects, the largest amplitude wave I occurred at the frontal electrode and for the fifth subject the largest wave I was

recorded at  $C_z$ . Second, the amplitudes of the positive waves II through V and the negative waves III through VI were generally largest near the vertex.

### The Latency of Auditory Brainstem Responses

The latencies of the ABR components change as a function of scalp location. TABLE 1A contains the mean values for three positions, ( $C_z$ ,  $M_c$ ,  $M_i$ ) referenced to a noncephalic site,  $C_{VII}$ . Components  $I_n$ ,  $II_n$ , and  $III_n$  could not be identified consistently at the ipsilateral mastoid ( $M_i$ ), and  $IV_n$  could not be identified consistently at the contralateral mastoid ( $M_c$ ). Percentage of subjects who demonstrated these components from these recording sites was 60% for  $I_n$ , 25% for  $II_n$ , 8.3% for  $III_n$ , and 33% for  $IV_n$ . All other components were identified in 90% or more of the trials. Examples of

TABLE 1  
MEAN LATENCY OF AUDITORY BRAINSTEM RESPONSE COMPONENTS (msec)\*

	I	$I_n$	II	$II_n$	III	$III_n$	IV	$IV_n$	V	$V_n$	VI	$VI_n$
<i>(A) Noncephalic Reference</i>												
$C_z-C_{VII}$	1.54	2.27	2.85	3.28	3.70	4.19	4.90	5.29	5.62	6.34	7.14	7.70
$M_i-C_{VII}$	1.53	†	2.81	†	3.80	†	4.74	5.32	5.77	6.39	7.16	7.72
$M_c-C_{VII}$	1.53	2.18	2.73	3.25	3.83	4.43	4.95	†	5.58	6.22	7.06	7.67
<i>(B) Differential Recordings</i>												
$C_z-M_i$	1.52	2.28	2.73	3.18	3.68	4.23	4.98	5.27	5.53	6.24	7.13	7.78
$C_z-M_c$	1.58	2.23	2.82	3.28	3.59	4.08	4.82	5.28	5.66	6.38	7.23	7.84
$M_c-M_i$	1.52	2.45	†	†	3.62	4.53	†	†	5.31	5.99	6.74	7.63
	$NP1_n$	$NP1$	$NP2_n$	$NP2$	$NP3_n$	$NP3$		$NP4_n$	$NP4$			
<i>(C) Nasopharyngeal Recordings</i>												
$NP_i-C_{VII}$	1.67	2.18	2.53	3.20	3.88	4.53		5.30	5.82			
$NP_c-C_{VII}$	†	†	†	†	3.65	4.40		5.20	†			

\*Click intensity, 65 dB SL; 11/sec stimulus rate; condensation polarity; 6 subjects (3 men, 3 women); each ear stimulated monaurally. Electrode placements:  $C_z$  = vertex;  $M_i$  = ipsilateral mastoid;  $M_c$  = contralateral mastoid;  $NP_i$  = ipsilateral nasopharynx;  $NP_c$  = contralateral nasopharynx;  $C_{VII}$  = seventh cervical spinous process.

†Components not evident in 10% or more of trials.

the waveforms from one subject and the grand average of all of the subjects are depicted in FIGURE 3. There are significant latency differences for wave II, III,  $III_n$ , IV, and V at these three sites (TABLE 2A). The magnitude of the mean latency differences at the three electrodes was quite small, ranging up to 0.24 msec. For each subject, wave IV at the ipsilateral mastoid occurred from 0.1 to 0.5 msec *before* wave IV recorded at the contralateral mastoid whereas wave V occurred from 0. to 0.6 msec *later* at the ipsilateral mastoid than at the contralateral mastoid. Viewed another way, the time separation between waves IV and V at the ipsilateral mastoid averaged 1.13 msec (range, 0.9–1.4 msec) while the separation of these waves at the contralateral mastoid averaged 0.5 msec (range, 0.3–0.7 msec). Such significant latency changes in the ABR components at the two mastoid recording sites can affect recordings using these sites as a "reference." For instance, in both Stockard *et al.*<sup>5</sup> and the present study, waves IV and V are more easily distinguished in recordings from  $C_z-M_c$  than from  $C_z-M_i$  (FIGURE 6). The enhancement of IV and V using the former derivation is

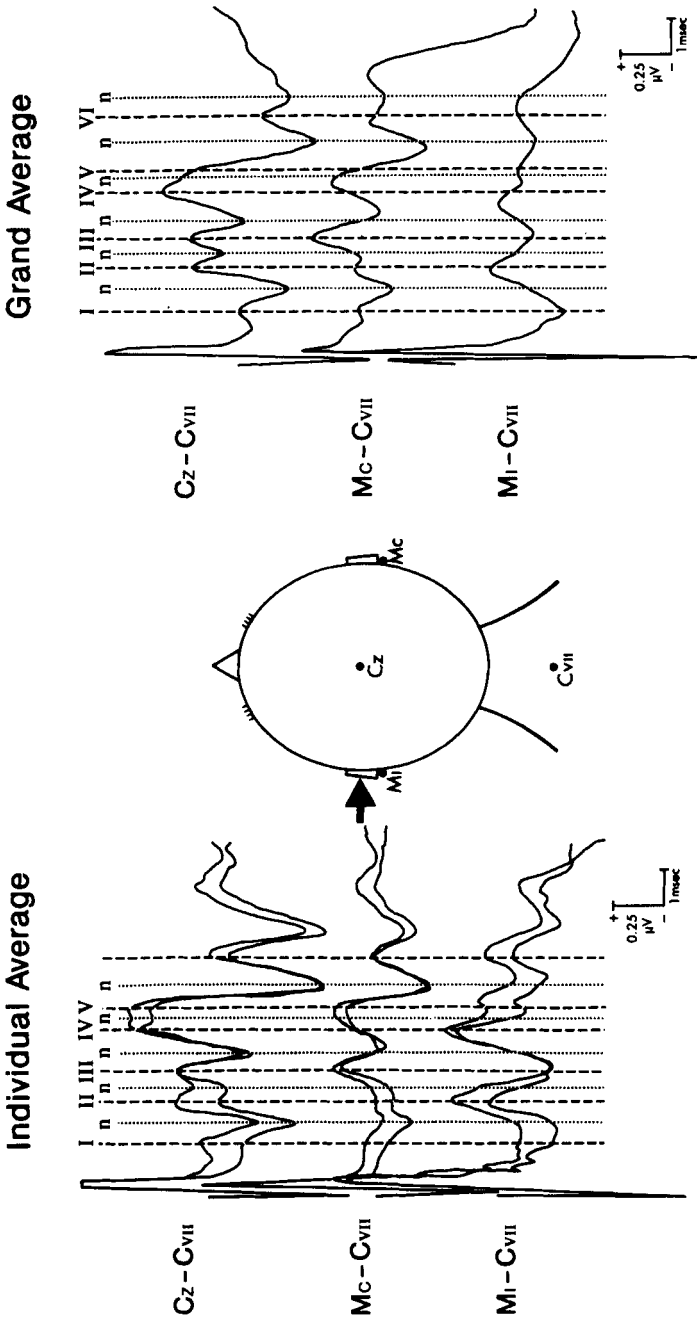


FIGURE 3. Auditory brainstem responses from both an individual subject and the grand average of six subjects recorded from Cz, Mc, and M1, all referenced to Cvii. In this and all subsequent figures, vertical lines descend through the components as defined at Cz. Two separate averages of 2000 click trials are superimposed in the individual average while the grand average comprises 4000 click trials from each of the six subjects. Note the polarity and latency changes in these three derivations.



due to differences in the temporal occurrence of the components recorded at  $M_C$  and  $C_Z$ . Wave IV peaks at  $C_Z$  before it does at  $M_C$  whereas wave V peaks at  $C_Z$  later than it does at  $M_C$ . The effect of amplifying these differences in a  $C_Z$ - $M_C$  recording is to enlarge the separation of waves IV and V. The difficulty of identifying *equivalent* peaks in differential recordings between two active sites is exemplified by the ABR derived from recording between the two mastoids,  $M_C$  referenced to  $M_I$  (FIGURE 6). During the time domain of the IV to V complex a component can be identified that falls intermediate between IV and V as identified at the vertex. There are no clear criteria to label such a peak at IV, IV<sub>n</sub>, or V.

### Nasopharyngeal Auditory Brainstem Responses

The brainstem potentials for the NP electrode referenced to the noncephalic electrode ( $C_{VII}$ ) are in FIGURE 4 both for an individual and for the grand average of all subjects. The figure also contains the standard  $C_Z$ - $C_{VII}$  recording. The positive peaks

TABLE 2  
SIGNIFICANCE LEVELS OF LATENCY MEASURES OF AUDITORY BRAINSTEM RESPONSE COMPONENTS\*

	I	I <sub>n</sub>	II	II <sub>n</sub>	III	III <sub>n</sub>	IV	IV <sub>n</sub>	V	V <sub>n</sub>	VI	VI <sub>n</sub>
<i>(A) Noncephalic Reference</i>												
$C_Z$ - $C_{VII}$ vs $M_I$ - $C_{VII}$	ns	†	ns	†	0.04	†	0.006	ns	0.002	ns	ns	ns
$C_Z$ - $C_{VII}$ vs $M_C$ - $C_{VII}$	ns	ns	0.05	ns	0.05	0.03	ns	†	ns	ns	ns	ns
$M_I$ - $C_{VII}$ vs $M_C$ - $C_{VII}$	ns	†	ns	†	ns	†	0.006	†	0.03	ns	ns	ns
<i>(B) Differential Recordings</i>												
$C_Z$ - $M_I$ vs $C_Z$ - $M_C$	ns	ns	ns	ns	ns	0.001	0.001	ns	0.06	0.03	ns	ns
	NP1 <sub>n</sub>	NP1	NP2 <sub>n</sub>	NP2	NP3 <sub>n</sub>	NP3		NP4 <sub>n</sub>	NP4			
<i>(C) Nasopharyngeal Recordings</i>												
$NP_I$ - $C_{VII}$ vs $NP_C$ - $C_{VII}$	†	†	†	†	0.03	0.001		ns	†			

\*See TABLE 1 for details. Values given are those of  $p$  (the probability of an incorrect hypothesis) as determined by the variance ratio,  $F$ . ns = not significant.

† $F$ -ratios not determined because of insufficient data.

at the nasopharynx have been labeled NP1 through NP4 and negative subscripts have been added in the preceding trough to designate the corresponding negative peaks. The potentials to ipsilateral stimulation consist of a prominent positive-negative-positive sequence of waves (NP2, NP3<sub>n</sub>, NP3) occurring in the time domain between components II<sub>n</sub> and IV as recorded at the vertex.

When the ear contralateral to the NP electrode was stimulated the potentials invert in polarity and shift to a slightly shorter latency (TABLE 1C). The NP brainstem potentials that occur before 3 msec and after 6 msec were greatly attenuated for contralateral stimulation so that consistent measures of peaks in those time domains were not possible. Subtracting the NP potentials to contralateral stimulation from those evoked by ipsilateral stimulation (bottom panel of FIGURE 4) resulted in a potential reflecting the time domain of differences in the two recordings.

In two subjects mapping of the nasopharynx was made to define the extent to which the latency and polarity of the NP potentials depend on electrode placement. Recordings were made when the electrode was inserted in the nasopharynx in the midline and when it was displaced laterally. This was done for each side of the

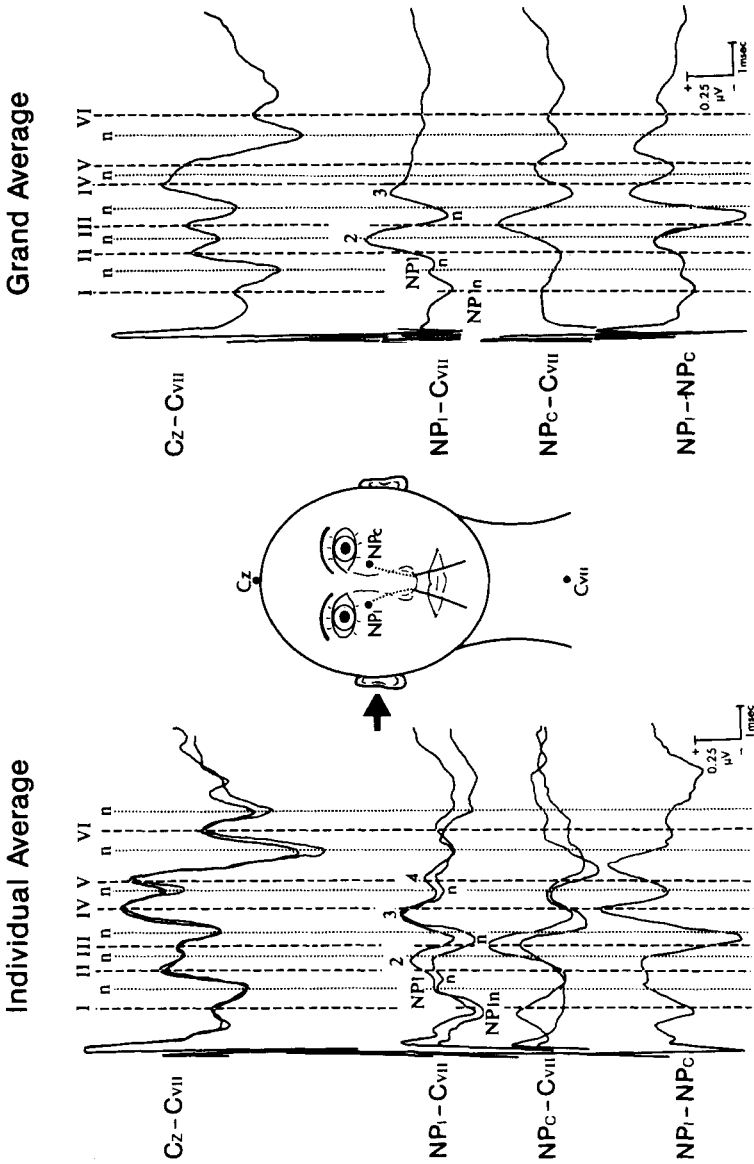


FIGURE 4. Auditory brainstem responses from both an individual subject and the grand average of six subjects recorded from Cz, the ipsilateral and contralateral nasopharynx (NP<sub>1</sub> and NP<sub>c</sub>, respectively) all referenced to Cvii. The difference potential between the two nasopharyngeal recording sites is in the bottom trace (NP<sub>1</sub>-NP<sub>c</sub>). The vertical lines descend through the components defined at Cz. The ipsilateral nasopharyngeal components have been labeled in sequence with arabic numerals and have the subscript *n* if the polarity is negative. Note the polarity and/or latency differences between the nasopharyngeal recordings.

nasopharynx. We estimate the separation of the electrodes across the midline to be 5 mm and the separation between the lateral and midline nasopharyngeal placements to be 3–5 mm. The results from the two subjects corresponded, and recording from four nasopharyngeal sites from one of the subjects are shown in FIGURE 5. Note that the electrodes in the same half of the nasopharynx record quite similar events but that recordings from either side of the midline change as a function of the site of stimulation as described previously.

It was of considerable interest to determine whether the potentials recorded at the scalp and at the nasopharynx were manifestations of the same neural events. A comparison of the various waves from FIGURE 6 suggests a correspondence between several of the scalp and NP recorded waves.

In the early portion of the waveform the ipsilaterally evoked nasopharyngeal waves NP1<sub>n</sub>, NP1, NP2, and NP3<sub>n</sub> had latencies approximating components I, I<sub>n</sub>, II<sub>n</sub>, and III recorded at the vertex, respectively. A major distinction between these two sites was that the components were of opposite polarity. In contrast, the polarity of the nasopharyngeal waves NP1<sub>n</sub> and NP3<sub>n</sub> to ipsilateral stimulation were the same as waves I and III recorded from the ipsilateral mastoid. Wave NP3 recorded from both the ipsilateral and contralateral nasopharynx corresponded most closely in latency to wave III<sub>n</sub> recorded from the contralateral mastoid, and waves NP4<sub>n</sub> and NP4 were of similar latency to waves IV<sub>n</sub> and V from the scalp. There were two events for which no correspondence could be defined: Wave NP2<sub>n</sub> from the ipsilateral nasopharynx occurred at a latency between waves I<sub>n</sub> and II at the scalp and wave IV at the scalp had no corresponding component from the nasopharynx.

*Auditory Brainstem Responses from Different Differential Scalp Montages*

FIGURE 7 contains the ABR recorded in four arrays from one subject and the grand average of all subjects: C<sub>Z</sub>-C<sub>VII</sub> (vertical montage), C<sub>Z</sub>-M<sub>I</sub> and C<sub>Z</sub>-M<sub>C</sub>

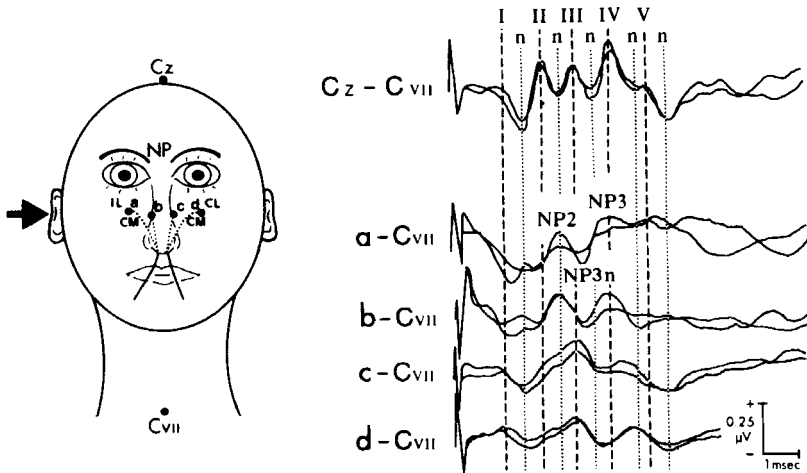


FIGURE 5. Auditory brainstem responses recorded from various positions within the nasopharynx referenced to C<sub>VII</sub>. Note the similarity of the potentials recorded on each side of the nasopharynx but the change that occurs on crossing the midline.

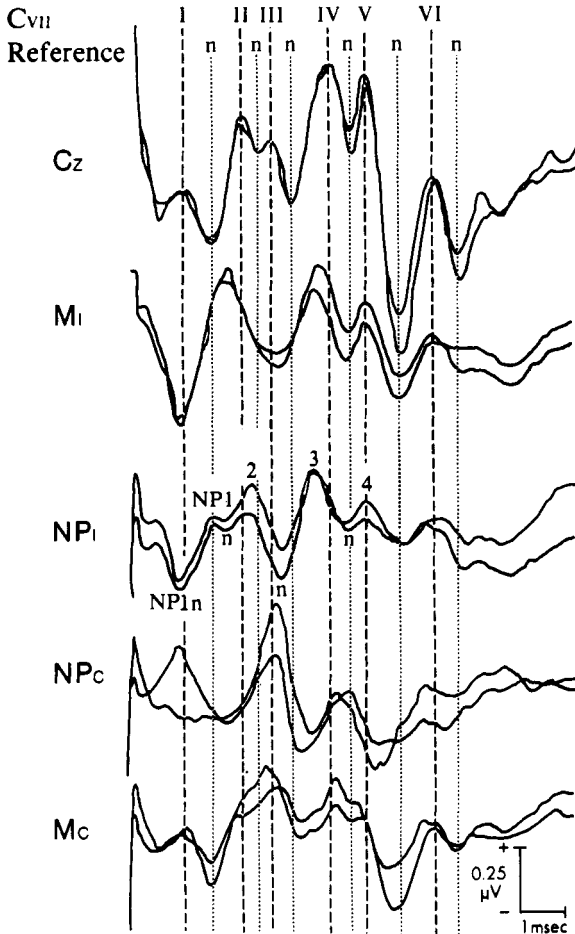


FIGURE 6. Auditory brainstem responses from an individual recorded from various scalp sites ( $C_z$ ,  $M_i$ , and  $M_c$ ) and the nasopharynx ( $NP_1$ ,  $NP_c$ ) referenced to  $C_{VII}$ . The vertical lines descend through the components recorded at  $C_z$ .

(diagonal montages), and  $M_c-M_i$  (horizontal montage). The mean latencies of the components are presented in TABLE 1B. Significance values for the latency differences between  $C_z-M_c$  and  $C_z-M_i$  are presented in TABLE 2B.

Wave I is easiest to define from the horizontal and one of the diagonal montages ( $C_z-M_i$ ). There may be no wave I when recording from the other diagonal montage ( $C_z-M_c$ ). Wave  $I_n$  is well seen in all recordings. Waves II and  $II_n$  are either indistinct or absent in the horizontal montage ( $M_c-M_i$ ) and are best visualized in the vertical ( $C_z-C_{VII}$ ) and one of the diagonal ( $C_z-M_c$ ) derivations. Wave III is particularly small in one of the diagonal montages ( $C_z-M_c$ ) and is of high amplitude and broad dimension in the horizontal montage ( $M_c-M_i$ ). This broadening of wave III reflects that the negative troughs surrounding III are both earlier and later in the horizontal derivation than in the other recording arrays. Wave  $III_n$  also occurs earlier in the

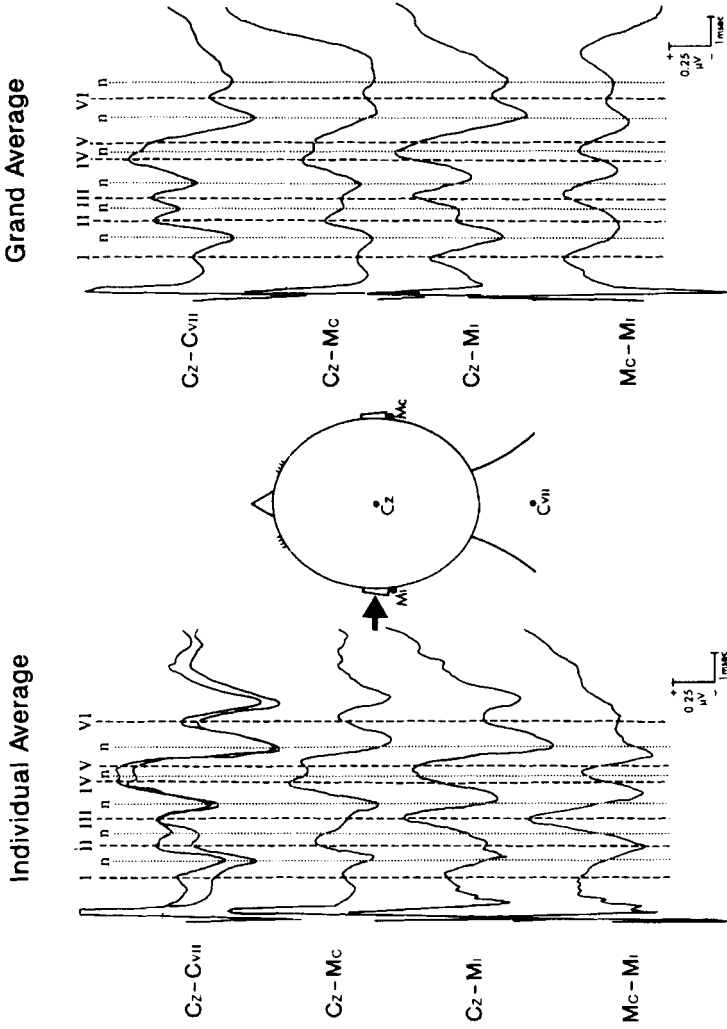


FIGURE 7. Auditory brainstem responses recorded from both an individual and the grand average of six subjects from several recording arrays; Cz-Cvii (vertical), Cz-Mc and Cz-Mi (diagonal), and Mc-Mi (horizontal). The vertical lines descend through the components defined at Cz-Cvii. Note that different components are recorded with different latencies and configurations in the various derivations.

$C_z-M_c$  montage than in the  $C_z-M_1$  array. The IV/V complex is particularly segregated into separate waves in the diagonal array,  $C_z-M_c$ , because wave IV occurs earlier and wave V occurs later in this array than in  $C_z-M_1$ . In the horizontal montage ( $M_c-M_1$ ), the IV/V complex appears as a low amplitude single component with a latency intermediate between the IV and V waves.  $V_n$  is well defined in the vertical and diagonal arrays and is of shortest latency from  $C_z-M_1$ . Finally, wave VI is attenuated in the horizontal recording array ( $M_c-M_1$ ).

## DISCUSSION

The aims of this study were: (1) to investigate further the distribution of amplitudes and latencies of the ABR over the scalp, particularly with regard to lateralization according to the stimulated ear; (2) to record ABRs referenced to a noncephalic site from the unique perspective provided by a nasopharyngeal electrode; (3) to define the ABR from several different montages that have clinical relevance. The findings with regard to these aims will be discussed for each of the ABR components.

*Wave I.* Recorded as a positive peak over most of the scalp, wave I has a negative polarity at the mastoid ipsilateral to stimulation. These results confirm those reported by several groups of investigators.<sup>2-4</sup> In addition to the lateral amplitude gradient, there is also an anterior-posterior gradient with the maximum mean wave I amplitude occurring frontally. At the nasion andinion the mean amplitude was essentially zero. The counterpart of wave I recorded from the ipsilateral nasopharynx (NP1<sub>n</sub>) has a negative polarity. On the basis of these data, the wave I field can be idealized as vectors in both the coronal and sagittal plane, with an origin located near the ipsilateral mastoid and nasopharynx. The current clinical recording method of recording between  $C_z$ , where wave I is positive, and the mastoid or earlobe ipsilateral to the ear stimulated where wave I is negative, clearly optimizes the detection of this component. In fact, wave I may be absent if recording vertex to the contralateral mastoid.

*Wave I<sub>n</sub>.* Recorded with largest amplitudes at the midline, particularly over the parietal scalp, this component was also lateralized. It was defined as a negative peak at the contralateral mastoid whereas at the ipsilateral mastoid it was either not identified or appeared as a positive inflection between waves I and II. The temporal counterpart of wave I<sub>n</sub> at the ipsilateral nasopharynx has a positive polarity (NP1). Thus, wave I<sub>n</sub> recorded at the ipsilateral mastoid and nasopharynx appears as a small positive wave while it is recorded as a pronounced negative wave over most of the scalp. Its generators have vectors similar to that of wave I.

*Wave II.* A positive peak at all scalp locations, wave II is largest at the vertex and parietal electrode sites. Thus, there is a progression from wave I, which is negative at the ipsilateral mastoid and positive at the vertex, to wave II, which is positive at all sites, with a "transitional" wave I<sub>n</sub> at the ipsilateral mastoid. This result has been noted by Terkildsen *et al.*<sup>3</sup>

The counterpart of wave II recorded from the ipsilateral nasopharynx (NP2<sub>n</sub>) was negative in polarity. Wave NP2<sub>n</sub> was not reliably recorded for contralateral stimulation.

These results are compatible with a dipole orientation of the generator(s) of wave II in the sagittal plane, since the amplitude of wave II showed no lateral asymmetry and the largest amplitudes tended to be recorded over the posterior scalp. This suggestion is supported by the polarity reversal between the ipsilateral mastoid and the more anteriorly situated nasopharynx electrode.

*Wave II<sub>n</sub>.* Wave II<sub>n</sub> was negative at all electrode sites and largest over the posterior scalp, but could not be distinguished at the ipsilateral mastoid where it blended with wave III. The nasopharyngeal counterpart (NP2) was of opposite polarity. In many respects, wave II<sub>n</sub> resembles wave II except in polarity and could be generated by similar mechanisms.

*Waves III and NP3<sub>n</sub>.* The scalp-recorded wave III has its maximum amplitude at the vertex, however it is markedly lateralized to the contralateral scalp, in agreement with Picton *et al.*<sup>2</sup> and Stockard *et al.*<sup>5</sup> At the ipsilateral mastoid, the mean amplitude of wave III is actually negative. The nasopharyngeal counterpart of wave III in terms of latency is wave NP3<sub>n</sub>. NP3<sub>n</sub> is also markedly lateralized and is negative for ipsilateral stimulation and positive for contralateral stimulation. The correspondencies between NP3<sub>n</sub> and III suggest the two events may be generated by similar processes. Wave III tended to be larger over the anterior than the posterior scalp. These results are consistent with the suggestion of Picton *et al.*<sup>2</sup> that wave III is the result of both vertically and horizontally oriented dipoles. The horizontal dipole reflected in wave III is situated medial to the ipsilateral nasopharyngeal electrode, and the vertically oriented dipole is directed slightly anteriorly. Moreover, the observation that the width of wave III is considerably broadened when recording from the horizontal plane (mastoid–mastoid) suggests a wide spatial extent of the horizontal dipole for the generation of this component.

*Waves III<sub>n</sub> and NP3.* The scalp derived wave III<sub>n</sub> was remarkable in its scalp distribution since it had no counterpart from the ipsilateral mastoid but did demonstrate a significant latency disparity between the vertex and contralateral mastoid. NP3 and NP3<sub>n</sub> were the most prominent peaks recorded from the nasopharynx. NP3 was markedly lateralized, being positive for ipsilateral stimulation. The significant latency disparity between NP3 to ipsilateral and contralateral stimulation is incompatible with a simple dipole source. NP3 to both ipsilateral and contralateral stimulation corresponds in latency to wave III<sub>n</sub> at the contralateral mastoid. Wave NP3 is likely a reflection of near-field brainstem activity of generators located slightly medial to the nasopharyngeal electrode as suggested by Martin and Coats.<sup>10</sup> Wave III<sub>n</sub> at the vertex may be a far-field reflection of this brainstem event.

*Wave IV.* Wave IV exhibited no significant amplitude lateralization, but tended to be largest over the anterior scalp. The latency of wave IV was earlier (mean: 0.24 msec; range: 0–0.5 msec) at the ipsilateral than contralateral recording sites. These results would be compatible with generators having vertical dipoles of short latency ipsilaterally and slightly longer latency contralaterally.

*Wave V and V<sub>n</sub>.* Wave V was positive and V<sub>n</sub> negative at all scalp locations and largest over the central and frontal sites. The latency of wave V was significantly delayed at the ipsilateral mastoid compared to the contralateral mastoid (mean difference: 0.27 msec; range: 0.1–0.6 msec). The values for wave V<sub>n</sub> were similar (mean difference: 0.23 msec; range: 0–0.5 msec), but did not achieve statistical significance. The absence of wave V and V<sub>n</sub> from the horizontal recording arrays (M<sub>C</sub>–M<sub>I</sub>) is consonant with vertically oriented dipoles for these components having significant latency disparity on both sides of the brainstem.

*Wave VI and VI<sub>n</sub>.* There was a general trend toward a greater negativity over the contralateral scalp, which was a significant only for wave VI<sub>n</sub>. This result is consistent with that reported by Martin and Coats.<sup>10</sup> The absence of wave VI in the horizontal array is compatible with vertically oriented generators.

The results of this scalp distribution study of the ABR in humans differ from similar mapping studies in monkey<sup>11</sup> and rat and cat.<sup>12</sup> In the animal studies there were significant changes in the number of ABR components as a function of scalp recording site. In the monkey, for instance, waves II and III at the vertex each

segregate into two distinct components with different lateral scalp distributions. In the present study in humans, the components did not break into separate subcomponents, possibly because of the large volume of the human skull relative to the brainstem, making the definition of various subcomponents difficult. In agreement with the animal studies, there were significant latency shifts of some of the components over the scalp in the human subjects. The latency shifts were maximum for waves IV and V but could also be distinguished for short latency events (wave II). The presence of latency shifts suggest that the generator sources comprising some of these components may move within the brainstem. The nerve action volleys traveling along fiber pathways could be a source of such moving generators.

The definition of latency disparities over the scalp is emphasized by differential recording arrays.<sup>5,6</sup> However, the interpretation of the mechanism of such latency shifts with differential recordings is complex since both sites are "active." It may be that the generator sites for components identified in such differential arrays are relatively specific for each array.

Both depth recording and lesion studies in animals<sup>13-15</sup> suggest that there may be multiple generator sites within the brainstem for many of the components of the ABR. The results from both the present study and other studies in humans<sup>2,3</sup> suggest that the generator sources for the ABR components can have different orientations and dimensions. Wave III, for instance, has both vertical and horizontal dipoles. Moreover, the broadening of component III in the horizontal montage suggests that the horizontal dipole is spatially extensive. These data from scalp recordings can be interpreted as indicating that the generators for some of the ABR components in man are not discrete but, rather, are spatially distributed.

The clinical use of ABR techniques is still in its beginnings. There has been reasonable success utilizing a single diagonal recording array (vertex-ipsilateral earlobe), and it has been suggested that the definition of abnormalities may be increased by utilizing other recording arrays.<sup>5</sup> In the present study *different values* for latencies of ABR components were obtained from recordings over the scalp in a horizontal, vertical, and two diagonal planes as well as sampling close to the brainstem itself from the nasopharynx. It is obvious that other arrays could also be defined. Thus, criteria need to be developed to allow critical judgment for the selection of the appropriate recording array(s) for clinical applications. We suggest the use of a single array (vertex-ipsilateral mastoid) may be suitable for most applications. However, in those instances when components are difficult to recognize the use of additional recording arrays may resolve the ambiguities.

Since the preparation of the manuscript, several articles relevant to the issue of scalp distribution of auditory brain stem potentials and the vectors of their generation have appeared.<sup>16-19</sup> The data in these articles expand our knowledge of possible generators of auditory brain stem responses.

#### SUMMARY

Auditory brainstem potentials were recorded from various scalp and nasopharyngeal sites referenced both to a noncephalic site and to certain scalp locations in normal humans. The distribution of amplitudes and latencies of the components were defined. There were significant amplitude, polarity, and latency asymmetries over the scalp in both referential and differential recordings. The data indicated that several of the ABR components have generator sources that are lateralized and move through the brainstem in particular orientations.



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