DERIVED WHOLE NERVE ACTION POTENTIALS IN RESPONSE TO LOW-FREQUENCY STIMULI

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ABSTRACT

Whole nerve action potentials were recorded from the round window of a single cat in an effort to obtain responses from the apical region of the cochlea. A 500-Hz signal was either 2 or 10 msec in duration, and was either presented at a low or high intensity. A high-pass masking noise, with cut-off frequencies of 1000, 3000, and 6000 Hz, was used in an attempt to eliminate activity from different frequency regions of the basilar membrane. The results suggest that particularly when a low-level, 10-msec duration signal was used, activity from the apical region predominated the response pattern.

INTRODUCTION

There has been considerable interest in using electrocochleography and brain-stem recordings to assess the integrity of the human auditory system, especially when conventional audiometric techniques are unsuccessful. However, the frequency specificity of these methods has been questioned (Davis, 1976). In particular, it is difficult to obtain electrical responses from low-frequency regions of the cochlea without stimulating high-frequency regions as well.

Placing an electrode on the round window allows us to measure the whole-nerve action-potential (AP), which consists of a summation of stimulus-evoked electrical activity. When high-frequency signals or clicks are used as stimuli, the traveling wave and resulting electrical activity are confined to the base of the basilar membrane (Teas, Eldredge, Davis, 1962). When a low-frequency sinusoid is presented to the cochlea, a traveling wave begins at the base and reaches a maximum near the apex (Bekesy, 1960). Particularly at high intensities, the entire length of the basilar membrane is set in motion. This is congruent with single fiber recordings from animal auditory nerves which show that fibers with high characteristic frequencies (originating from the base) also respond to low frequency stimuli (Kiang and Moxon, 1974). One would expect that the low-frequency evoked AP reflects activity from the entire basilar membrane.

The importance of obtaining low-frequency information has prompted recent authors to devise methods to accomplish this task. We shall use a high-pass masking paradigm, first employed by Teas **et al.** (1962). With this method, AP responses are obtained in the presence of high-pass masking noises of different cut-off frequencies. Suppose we obtain AP's in the presence of two high-pass noises, with 1000 and 3000-Hz cut-off frequencies. The AP obtained with the 1000-Hz high-pass noise reflects activity from regions representing frequencies **less than** 1000 Hz. When the 3000-Hz high-pass noise is used, the AP reflects activity from regions representing frequencies **less than** 3000 Hz. If we subtract, point by point, the AP waveform obtained in the presence of the 1000-Hz high-pass noise from the AP obtained with the 3000-Hz high-pass noise, the resulting waveform should be representative of frequency regions between 1000 and 3000 Hz. The underlying assumption is that the high-pass noise has eliminated synchronous activity from frequency regions higher than the cut-off frequency. We shall examine these **derived** waveforms in a cat by measuring the AP to 500-Hz signals.

METHOD

Preparation

A cat weighing 2.3 kg was anesthetized with 1.75 cc of Nembutal and treated with Atropine (0.2 cc). Additional Nembutal was given as needed. A tracheotomy was performed and body temperature was maintained with a heating pad. The bulla was opened and a steel electrode placed in contact with the promontory. A ground electrode was positioned in the back of the neck. A click-evoked AP was obtained intermittently to monitor the cat's response stability.

Stimuli

Our 500-Hz signal conditions contained two durations and two intensities. We selected two durations because of their differences in energy spectra (the longer duration signal has more energy at 500 Hz), and because differences might be reflected in the temporal pattern of the AP. Two intensities were used to enable us to evaluate differences caused by the spread of excitation (the higher intensity signal produces a larger area of excitation). The durations were either 2 msec (between 50% points on the signal envelope) with 1 msec rise/fall times or 10 msec with 2.5-msec rise/fall times. The intensities were either 5 or 25 dB above the level where the AP was just visually detected on the oscilloscope by the experimenter. These levels were 83 and 103-dB SPL (re: 20 μPa) (with the signal on continuously) for the 5 and 25-dB conditions respectively, for both signal durations.

The noise was on continuously throughout each duration-intensity condition. The noise level was set so that each unfiltered noise just masked the visual detection of the AP evoked for the particular signal in question. High-pass filtering was introduced keeping the spectrum level in the pass-band constant. The overall SPL of the unfiltered noise was 57, 87, 72, and 87 dB for the 2-msec low and high-level, 10-msec low and high-level conditions respectively. Cut-off frequencies were 1000, 3000 and 6000 Hz at the 3-dB down points and rejection slopes were 96 dB per octave.

Averaging

Each AP was obtained by averaging responses to 1000 presentations. When recording AP from the round window, we need to eliminate the cochlear microphonic (CM) and electromagnetic artifacts originating from the earphone (Feinmesser and Sohmer, 1976). This is usually accomplished by reversing stimulus polarity on half of the trials or presenting the stimuli at random phase onsets. The AP will shift latency (by one half period of the stimulus) when the polarity is reversed, which means that AP recordings will not superimpose in time when they are averaged. We decided to reverse polarity and interpret the AP waveforms in this light. Data points were obtained every 100 msec for each recording. Interstimulus intervals were always 200 msec.

Apparatus

A Hewlett-Packard (H-P) 200 CDR oscillator generated the signal, which was then gated by a Grason-Stadler (G-S) 829-E Electronic Switch. The switch was triggered with a G-S E3299a Interval Timer. A G-S 455-B Noise Generator provided the noise which was then filtered by a Krohn-Hite 3343R filter (two high-pass sections cascaded). Both signal and noise passed through separate H-P 350-C Attenuators, and were then passively mixed, lead to a United Transformer Corp. LS-34 transformer and a shielded

Koss Pro 4AA earphone. A metal tube sealed the earphone to the external meatus. The cat was situated in an International Acoustics Corp. double-walled sound room.

Recordings from the electrode were lead to a Grass P18 Micro-electrode DC Amplifier, a Tektronix RM-122 Low Level Pre-amplifier, a Biomedical Electronics WD 117 Discriminator and to an Interdata 4 minicomputer. On-line CM and AP and averaged responses were monitored on a Tektronix 549 Storage Oscilloscope.

Levels were measured at the eardrum with a Bruel and Kjaer 4134, ½ inch microphone with a probe inserted through a small hole in the tube connecting the earphone to the external meatus.

RESULTS

The results from the 2-msec, low-level signal are shown in Fig. 1. The top waveform is the response to the unfiltered signal. The second waveform was derived by subtracting the AP obtained with the 6000-Hz cut-off noise from the top waveform. The third waveform was derived by subtracting the AP obtained with the 3000-Hz cut-off noise from that obtained with the 6000-Hz cut-off noise. Similarly, the fourth waveform was derived by subtracting the 1000 from the 3000-Hz cut-off noise. The bottom waveform represents the response obtained with the 1000-Hz cut-off noise. Waveforms of Fig. 2 through 4 were obtained in a similar manner.

The vertical bar in the upper left hand corner of all figures represents 3 μV. Time on the abscissa is relative to signal onset.

The distances along the BM represented by the different frequency regions (shown at the right of each figure) are not equal. We can examine the data of Schuknecht (1960) to compare these distances. In twenty cats he studied, the average length of the BM was 21 mm. The regions most sensitive to frequencies higher than 6000 Hz represent about 40% of this total. Similarly, the 3000 to 6000-Hz region represents 10%, the 1000 to 3000-Hz region represents 20%, and the region less than 1000 Hz represents about 30% of this distance. We expect the magnitudes of the derived waveforms to differ accordingly.

In Fig. 1 activity from the entire BM contributed to the unmasked AP. As the high-pass noise cut-off frequency was lowered, the maximum negative peak in the waveform shifted in time. The waveform representing the region less than 1000 Hz reached its peak more than 1-msec after the unmasked response reached its maximum peak.

Fig. 2 displays the waveforms for the higher-level, 2-msec duration signal. Again we see that activity was recorded from the entire BM. The maximum negative peak of the derived waveforms shifted as the cut-off of the noise shifted. This delay is just under 1 msec for the 1000 to 3000-Hz region compared to the unmasked response. When the cut-off was lowered to 1000 Hz, the waveform contained several peaks which lasted the entire duration of our sample, suggesting that this is an uncanceled response to noise. This obscured the clarity of our response from the region less than 1000 Hz, although the maximum peak was still observed to shift in time. A larger number of samples should have eliminated the response to the noise.

Fig. 3 and 4 display the results for the 10-msec duration signal. Fig. 3 shows the waveforms for the lower level signal. It is apparent that a large portion of the activity is from the 1000 to 3000-Hz region, and even more from the region less than 1000 Hz. In addition, the maximum negative peak for the less than 1000-Hz region occurs almost 1.8 msec after the peak in the unmasked response. We avoid using the term 'N1' with our data as we feel it is more profitable to examine the entire response. This is especially true

for signals with long durations and slow rise/fall times. In Fig. 3, we see that the entire pattern of activity from the >6000-Hz region occurs at an earlier time and with less magnitude than the entire pattern of activity of the < 1000-Hz region.

Fig. 4 displays the higher intensity, 10-msec duration signal. Unfortunately we were not able to increase our noise level to completely mask the visual-detection threshold for this signal, and we therefore believe that we had not succeeded in eliminating the basal turn response. The waveform from the region greater than 6000 Hz is very nearly the same as the unmasked waveform, indicating that the electrical activity recorded from this signal was primarily from the basal turn. The observation that the response from the 1000 to 6000-Hz region and from the region of less than 1000 Hz are very similar, is consistent with our hypotheses that we did not have sufficient masking and were recording activity from the basal turn.

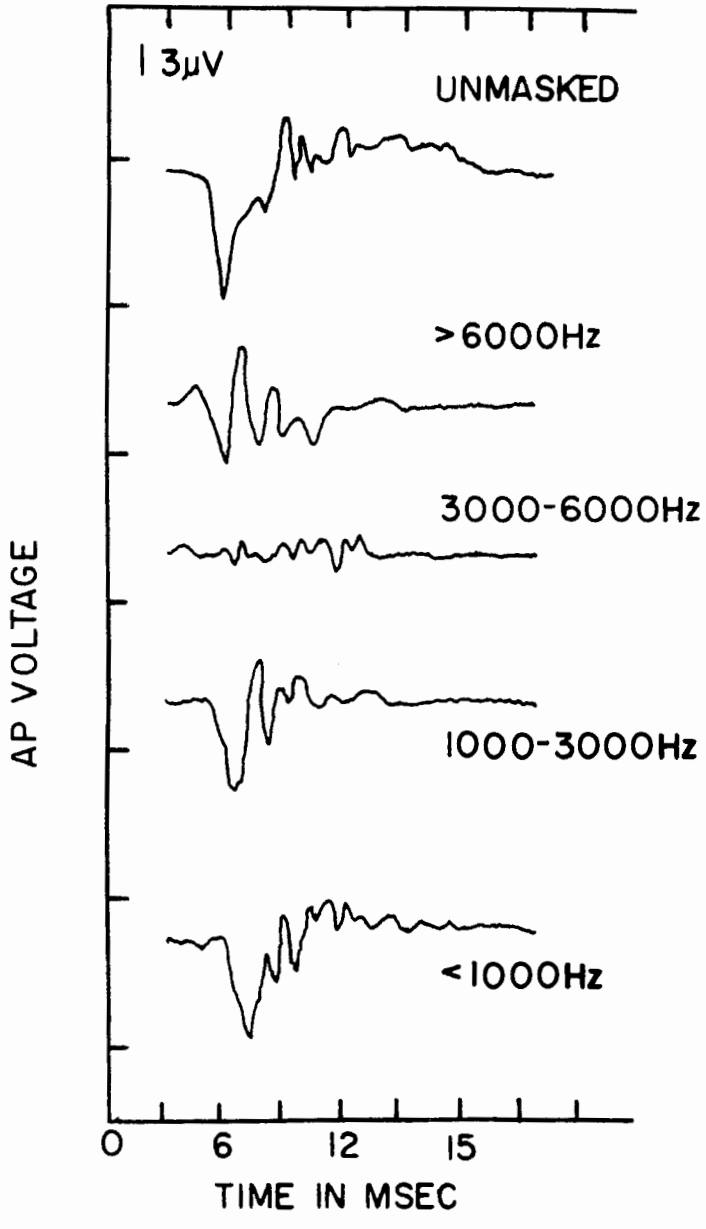

Figure 1: Waveforms for the 2-msec, low-level signal. The top waveform is the unmasked AP. The bottom waveform is the AP obtained in the presence of a 1000-Hz cut-off, high-pass noise. Middle waveforms are derived (see text for details). Frequency intervals on the right signify the regions on the basilar membrane from which the derived activity originates. Figure 2 through 4 have the same interpretation.

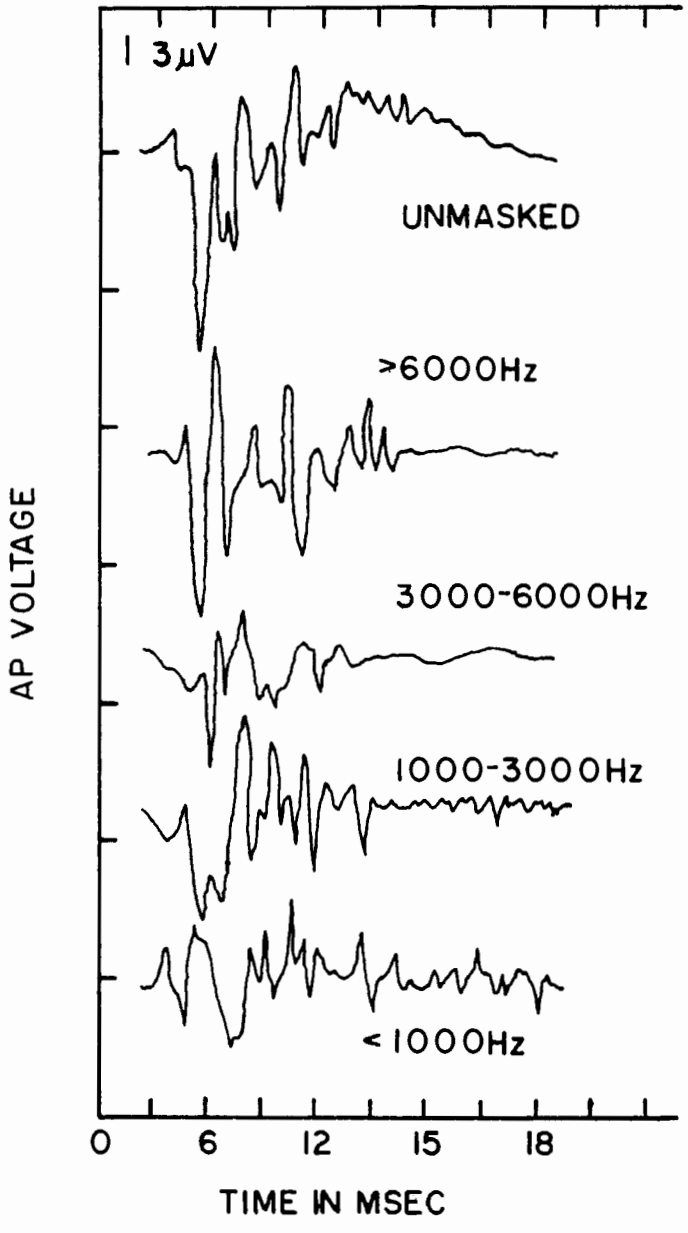

Figure 2: Waveforms for the 2-msec, high-level signal. (See caption with Figure 1 particulars).

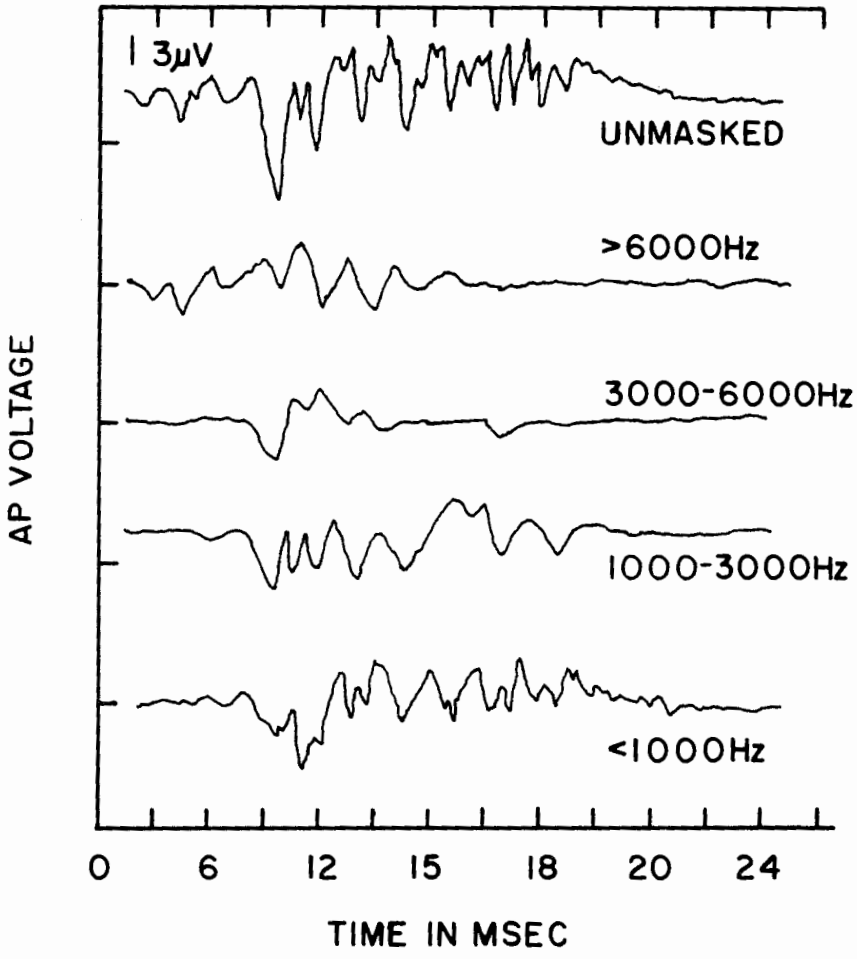

Figure 3: Waveforms for the 10-msec, low-level signal. (See caption with Figure 1 for particulars).

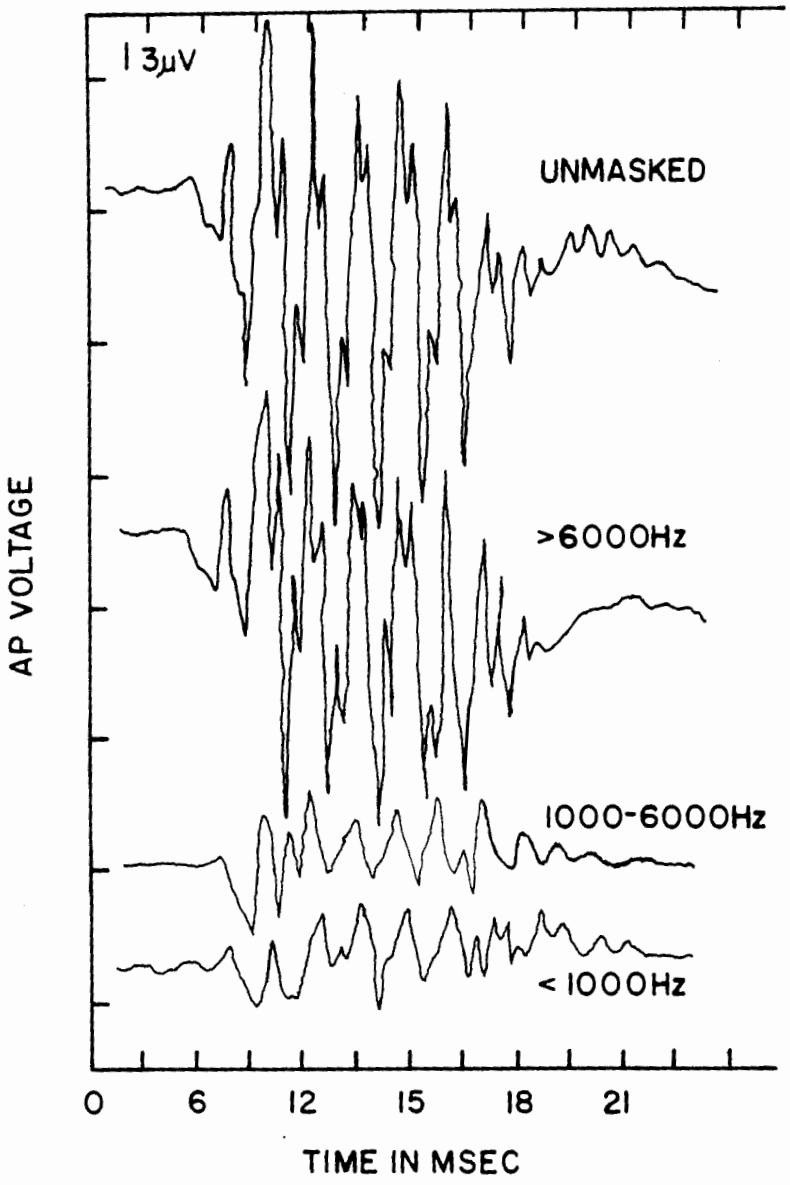

Figure 4: Waveforms for the 10-msec, high-level signal. (See caption with Figure 1 for particulars).

DISCUSSION

We have obtained electrical activity from different frequency regions of the BM in response to a 500-Hz signal. Generally, activity from the entire length of the BM contributed to the unmasked AP. With a 2-msec signal, a large amount of the activity was from the basal regions. However, responses from the apical 30% of the BM could be separated with the high-pass masking technique. Responses from the apex were delayed in time with respect to activity recorded from the base.

When a higher-intensity, 10-msec signal was used, the AP recorded was essentially that obtained from the basal end of the cochlea. When a lower-level, 10-msec signal was used, the entire response pattern was dominated by the apical region (Fig. 3). Thus our data indicate we can separate activity from different frequency regions when a low-frequency (500 Hz) signal is used.

Other researchers have also used this high-pass masking strategy. Bone, Crowley, and Rauchbach (1972) obtained click responses from rats and guinea pigs, and Elberling (1974) applied click stimuli to humans. Consistent with the Teas **et al.** data, activity recorded with click stimuli predominantly arises from the base of the BM. Eggermont (1976) and his colleagues have reported derived responses with tonal stimuli, but usually with higher-frequency signals (2000 Hz).

At least two groups have presented low-frequency signals to humans. Zerlin and Naunton (1976a, 1976b) used one-third octave band clicks, and report N_1 latency for center frequencies at octave intervals from 250 to 8000 Hz. They showed an increase in latency of about 1.7-msec between a 1000 and an 8000-Hz center-frequency signals, which is consistent with our data. The time of occurrence of their N_1 for signal frequencies less than 1000 Hz is not very clear (see their Fig. 3; 1976a), and we suggest N_1 is not a useful parameter for these recordings.

Davis and Hirsh (1976) recorded brainstem response from humans using short (1-cycle rise and fall with no envelope plateau) and long duration (4 to 6 cycle) 500-Hz signals. Their results were similar to ours in that only the recorded activity to low-level signals reflected apical turn activity.

A drawback of this technique, related to non-linearities of the ear, needs to be mentioned. We expect the auditory system to produce distortion products—combination bands (Greenwood, 1971)—in response to a high-pass noise. Some of these distortion products will be in the low-frequency regions. Thus the effects of the high-pass masker will not be limited to the basal region. In addition, effects similar to those observed in two-tone suppression (Sachs and Kiang, 1968) may cause the noise, or its distortion products, to reduce the neural activity in apical regions. It is difficult to assess the degree to which these non-linear effects limit our interpretation that the derived waveforms represent responses from certain frequency regions along the basilar membrane.

In conclusion, an unmasked AP to low-level, low-frequency stimuli can reflect activity from the apical turn of the BM. We realize that our limited data from one cat is only preliminary, but they are encouraging and we hope will motivate others to utilize low-frequency stimuli.

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ACKNOWLEDGEMENT

We wish to thank Neil Shepard for guidance in the computer processing of the data, Jerry Yanz for his assistance in preparing the animal, and Paul Abbas for his comments on the manuscript.

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