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COCHLEAR INITIATION SITES OF THE HUMAN AUDITORY
FREQUENCY FOLLOWING POTENTIALS

The University of Arizona

PH.D.

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COCHLEAR INITIATION SITES OF
THE HUMAN AUDITORY FREQUENCY FOLLOWING POTENTIALS

by
John Charles McDermott

A Dissertation Submitted to the Faculty of the
DEPARTMENT OF SPEECH AND HEARING SCIENCES
In Partial Fulfillment of the Requirements
For the Degree of
DOCTOR OF PHILOSOPHY
In the Graduate College
THE UNIVERSITY OF ARIZONA

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THE UNIVERSITY OF ARIZONA
GRADUATE COLLEGE

As members of the Final Examination Committee, we certify that we have read
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FREQUENCY FOLLOWING POTENTIALS

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for the Degree of DOCTOR OF PHILOSOPHY.

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A handwritten signature in cursive script, appearing to read "John C. McDermott", is written over a horizontal line.

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ABSTRACT

The frequency following potential (FFP) is an auditory evoked response which crudely replicates the waveform of the stimulus. The origins of this far-field potential have been localized to the cochlea and specific auditory nuclei. The initiation site of the FFP along the cochlear partition has been thought to be dependent upon stimulus sound pressure level. Low stimulus levels elicit FFP from the apical turn of the cochlea, while moderate and high stimulus levels may elicit FFP from a large segment of the partition, including the basal turn. Simultaneous masking studies have contributed to the knowledge of this potential, but results from these studies may be confounded by interference from bioelectric potentials generated by distortion products from the masking noise.

This investigation used non-simultaneous masking tones set at the subject's pulsation threshold level (PTL). This psychophysical method provides a representation of the frequency-resolving properties of the auditory periphery in a repeated gap masking paradigm. Patterns of the relative masking effect of each masking tone were plotted and compared for several probe levels and in the presence or absence

of a continuous, high-pass masking noise. Tuning patterns derived in high-pass masking noise effectively represented apical turn FFP. Those patterns without masking noise represented whole-cochlea FFP.

The results of this study demonstrated tuning patterns that reflected diminished FFP amplitudes in the primary 500 Hz region as well as in an extended secondary range of 800 to 2000 Hz, depending on the stimulus-masking parameters. Tuning patterns in high-pass masking noise were consistently flatter in the primary and secondary regions than for the tuning patterns without masking noise. The secondary regions of the tuning patterns extended above 2000 Hz for the patterns obtained without high-pass masking. Tuning patterns were consistently broader for the high stimulus level than for the moderate stimulus level.

The multiple cochlear initiation sites for the FFP preclude its use as an audiological tool for the assessment of low-frequency hearing. However, the potential is suggested as a method to assess whole-cochlear response for the difficult-to-test patients with suspected profound hearing loss.

INTRODUCTION

Realizing that behavioral assessment of auditory function may be difficult because of limited patient response proclivity, audiologists have sought electrophysiologic measurement techniques which do not require the cooperation of the difficult-to-test patient. In recent years, several types of auditory evoked potentials have emerged as candidates for indices of auditory function. The short-latency, auditory brainstem response (ABR) and the frequency following potential (FFP) are two classes of responses which have attracted much attention recently.

The ABR is a bioelectric event associated with synchronous discharge of onset-sensitive neurons in the peripheral and central auditory pathways. Among early reports of ABR characteristics, Sohmer and Feinmesser (1967) described ABRs as having four sequential peaks extracted from ongoing electroencephalographic (EEG) activity during the first 6 msec after the presentation of an unfiltered click stimulus. Jewett and Williston (1971) noted seven vertex-positive peaks extending to 8 msec under similar stimulus conditions.

Both pairs of investigators speculated about the neural origins of these potentials. Sohmer and Feinmesser

suggested that the first two peaks represent separate discharges of different cell populations in the auditory nerve. Successive peaks were thought to be iterative firings of the auditory nerve, or of the lower brainstem auditory nuclei. Jewett and Williston stated that the first wave is generated by the action potentials of the eighth nerve. They argued that wave II arises from the cochlear nuclei, and subsequent waves are "composites from multiple generators, both ascending and descending . . . in algebraic summation" (Jewett and Williston, 1971, p. 692).

One factor restricting the use of ABR in the assessment of hearing sensitivity is that the normal response is due to the activation of the receptors at the basal end of the cochlea. This restriction occurs because transient stimuli must be used to elicit clear ABRs. Consequently, application of ABR to a clinical population has been restricted to assessing the sensitivity of onset-sensitive neurons which are responsive to high-frequency stimulation. Only very recently has an elaborate masking scheme (Teas, Eldredge and Davis, 1962) been adapted to provide derived-responses from selected areas of the human basilar membrane, including the apical end of the cochlea (Don, Eggermont and Brackmann, 1979). However, this method for obtaining frequency-selective information regarding cochlear sensitivity is expensive, time-consuming and not feasible for most clinical environments.

The FFP is regarded by some investigators as a putative electrophysiologic measure of the cochlear apical region (Moushegian, Rupert and Stillman, 1973; Yamada, Yamane and Kodera, 1977). The FFP is manifested as a cyclical EEG voltage fluctuation that appears as a crude replica of the waveform of the eliciting stimulus (Worden and Marsh, 1968). FFPs are observed in humans for 500 Hz tonal stimuli at levels as low as 15 dB Sensation Level (SL) (Glaser et al., 1976).

If the FFP has a cochlear initiation site in the apical region, the utility of this response as an index of low-frequency hearing sensitivity might be important. However, if it can be demonstrated that the basal end of the cochlea contributes a major component to the FFP for low-frequency stimuli, serious reservation would be placed on the FFP as an assessment tool for low-frequency hearing sensitivity.

Two methods have been employed to investigate the cochlear initiation sites of the FFP: simultaneous-masking studies, and the examination of clinical populations with frequency-selective hearing loss. Investigators who used masking to explore the cochlear initiation sites of the FFP concur that the FFP appears to be broadly generated from the apical-third of the cochlea at low and moderate stimulus levels (Gardi, 1978). At high stimulus levels, the FFP

cochlear initiation site seems to extend from the apical to basal regions (Davis and Hirsh, 1976).

Observing FFP records from subjects with hearing loss, researchers have reported good agreement between the patient's audiogram in the low-frequency region and the threshold for low-frequency FFPs. However, the high-frequency segment of the audiogram and the threshold for low-frequency FFPs showed no correlation in the same subjects (Yamada et al., 1978).

Hence, an unambiguous interpretation of FFP responses has not been possible due to conflicting evidence regarding the probable cochlear initiation sites for the FFP. The review which follows describes the features of the FFP, surveys attempts at the identification of its neural origins, and provides a rationale for a methodology which may determine its cochlear initiation sites.

REVIEW OF THE LITERATURE

Generators of the FFP

Investigators of the FFP do not agree upon the anatomical source for this potential. Some researchers consider the FFP to represent a crude envelope of some aspect of the electric activity of single cells within the brainstem (Worden and Marsh, 1968). Others suggest a purely cochlear origin for the FFP (Hou and Lipscomb, 1979). However, the majority of the investigators of this potential concur that both the auditory brainstem and the cochlea contribute to the generation of the FFP.

The Brainstem

Early investigators of the FFP recorded from gross electrodes implanted within auditory and non-auditory brainstem nuclei of the cat. Worden and Marsh (1968) were able to record FFP only at sites within, or very near, the classical auditory pathways. Responses from electrodes were observed in the cochlear nucleus (CN), the superior olivary complex (SOC), the nuclei of the lateral lemniscus (NLL), and the inferior colliculus (IC), but not within brainstem sites rostral to the IC. The FFP has been recorded from the ventral portion of the medial geniculate body (MGB). However, this portion of the MGB receives direct fibers from

the NLL, and the intracranial FFP is considered to originate from NLL fibers which have bypassed the IC (Weinberger, Kitzes and Goldman, 1970).

Marsh, Worden and their colleagues investigated the generator sites of the far-field FFP in cats. Worden and Marsh (1968) and Marsh, Worden and Smith (1970) considered that the far-field FFP was neurogenic rather than a volume-conducted cochlear microphonic (CM), or a stimulus artifact for three reasons:

1. The frequency range over which the FFP occurs was narrower than the range for the CM.
2. The FFP disappeared immediately with other neuro-electric activity during asphyxia, while the CM continued for a period of time afterwards.
3. The FFP was abolished with sectioning of the auditory nerve or CN cooling with a cryoprobe, while the CM remained undisturbed.

Marsh, Smith and Worden (1972) noted that the addition of an increasingly more intense masking noise to a tone burst resulted in reduced amplitude in far-field FFP. They interpreted this amplitude reduction as a desynchronization of phase-locked neurons in the cochlear nuclei.

In a series of lesion investigations, Marsh, Brown and Smith (1974) demonstrated two discrete pathways for the conduction of FFP from the CN to the IC:

1. Directly from the CN via the contralateral LL to the contralateral IC.
2. From the CN via the ipsilateral SOC and the LL to the ipsilateral IC.

Smith, Marsh and Brown (1975) performed cryosurgical studies in cats in which they cooled the contralateral IC and recorded simultaneously with electrodes from the vertex, the ipsilateral medial superior olive (MSO) and both the contralateral and ipsilateral IC. They found that the vertex-recorded FFP diminished to a small portion of the pre-cooling amplitude when the IC temperature was reduced. The vertex-recorded FFP returned to pre-cooling amplitudes after the IC was permitted to return to normal body temperature. Smith and co-workers concluded that the IC was responsible for the generation of the far-field FFP.

Gardi, Merzenich and McKean (1979) measured percentage of amplitude change in far-field FFP when the various auditory nuclei were aspirated in a descending sequence. They found that the FFP amplitude reduction was insignificant when the contralateral IC was ablated. When the structures between the contralateral IC and the ipsilateral CN were ablated, the FFP amplitude reduced to about 50% of the pre-surgical amplitude. These researchers considered that the data supported a CN site for the generation of the neural component of the FFP, and discounted the participation of the IC.

The Cochlea

One pair of investigators concluded that the FFP does not originate in the brainstem, but is the CM detected by far-field electrodes. Comparing recordings from surface and round window sites in chinchillas, Hou and Lipscomb (1979) noted:

1. The latency difference between FFP and CM onset was "in the microsecond range."
2. Post-mortem FFP and CM amplitudes diminished at comparable rates over a 60-minute period.
3. FFP and CM waveforms and phase angle did not change during the post-mortem recording session.

In the same report, Hou and Lipscomb conceded that FFP may contain auditory nerve electric potentials as well as other unidentified neural components. The auditory nerve component of the FFP was susceptible to masking noise. Other neural components were not addressed by Hou and Lipscomb, but were investigated by Sohmer and his associates.

The Cochlea and the Auditory Brainstem

Sohmer and Pratt (1977) and Sohmer, Pratt and Kinarti (1977) claimed to identify a non-neural (CM) and a neural component of the FFP. They recorded FFP to high sound pressure level (SPL) tone bursts and observed a response with a latency of about 1 msec. The latency was identical to the onset of the surface-recorded CM response. The FFP

inverted when the polarity of the tone burst was reversed. The apparent CM component was deleted when the average FFP to one polarity was added to that of an equal number of presentations of the stimulus in the opposite polarity. A remaining sinusoidal response was smaller and less well formed, had a longer latency, a periodicity twice that of the stimulus, and was assumed to be of neural origin. Sohmer and Pratt (1977) concluded that the FFP is composed of a short-latency CM component and a smaller neural component which has a longer latency when a high SPL stimulus is used.

Gardi, Merzenich and McKean (1979) reported that the CM recorded at the promontory of normal ears in cats was identical in latency to that of the scalp-recorded FFP. Observing FFP records made at death and 30 minutes post-mortem, they reported a loss of amplitude in both the CM and the FFP. Gardi and his associates interpreted these amplitude changes as predictable reductions in the CM component of the FFP.

In addition, Gardi, Merzenich and McKean (1979) performed a series of ablation studies in cats during which successively lower auditory nuclei were aspirated. After aspiration of the contralateral IC, the acoustic striae, and the ipsilateral CN, the remaining FFP amplitude was about 25% of the pre-surgical, far-field FFP. They concluded that CM is an appreciable component of the FFP.

Though studies by Sohmer and associates and by Hou and Lipscomb agree qualitatively with the evidence Gardi and his colleagues provided, species and procedural differences may have contributed to the different quantitative outcomes. Nonetheless, recording at the surface of the scalp in man, cat or chinchilla results in small, rapid-onset potentials interpreted as cochlear potentials.

Gardi, Merzenich and McKean sought to identify the neural components of the FFP. They observed that the far-field FFP amplitude envelope waxes and wanes systematically as a function of the stimulus frequency. The researchers noted:

1. Maximal amplitudes in FFP at 800-1000 Hz, and at 1600-1800 Hz.
2. Minimal amplitudes in FFP at 400 Hz, 1200-1500 Hz, and 2000-2500 Hz.

Gardi and his colleagues calculated that such cyclical changes in FFP amplitude as a function of stimulus frequency could result from volume-conducted electric activity from several neural generators. The individual generators would have response latencies located 1.25, 3.75 or 6.25 msec apart. In order to demonstrate this principle, these researchers modelled an FFP by adding on a summing computer three tone bursts of identical frequency, but with delayed onsets. The second and third tone bursts were delayed 1.25

and 3.75 msec with respect to the first tone burst, and the frequency of the tone bursts were varied in 100 Hz increments from 300 to 3000 Hz. The simulated FFPs yielded a sequence of waveforms with envelopes which waxed and waned with maxima and minima that were similar to those of the actual far-field FFPs in cats.

Smith et al. (1975) reasoned that if there are multiple generators for FFP, then each site would contribute synchronous, phase-locked discharges with different latencies when recorded at the surface of the skull. As frequency of stimulus increases, response phase effects will manifest themselves in the resultant FFP as a waxing and waning of the averaged waveform. Smith et al. recorded simultaneously from the CN, the MSO, and the IC, and presented tone bursts of various frequencies. The data from this study supported the notion of multiple generator sites when the investigators noted changing phase angles between FFP recorded at each of these brainstem levels.

In summary, the generators contributing to the far-field FFP have been considered to include the cochlea and at least one neural aggregate. Some researchers have considered the FFP to be entirely CM in at least one mammalian species, the chinchilla (Hou and Lipscomb, 1979). The CN appears to be one of the neural generators for far-field FFP, but a controversy still exists concerning the participation of the

IC in the FFP. There are other neural aggregates between the CN and the IC that may participate in neural FFP.

Some investigators have suggested that there are two monaural, independent, and non-iterative FFP generators that follow the classic, ipsilateral and contralateral ascension of the auditory pathways at least up to the level of the IC (Gerken et al., 1975). Evidence of the neurogenic bases for these potentials and the manner in which the neural centers may interact to produce the FFPs has not been demonstrated unequivocally.

Cochlear Initiation Sites of the FFP

Simultaneous Masking Studies

Most investigators suggest that the FFP obtained for low-frequency stimuli at low SPLs is initiated from the apical third of the cochlea (Gardi and Merzenich, 1979), and not from a narrow, restricted region on the basilar membrane (Yamada et al., 1979). At higher SPLs the tone bursts excite the entire cochlear partition. However, because of the properties of the traveling wave, the basal end of the cochlea responds with relatively little temporal dispersion and with an earlier onset than the apical turn of the cochlea.

Investigations into the cochlear initiation sites of the FFP in humans have taken two general directions:

1. Recording FFP from normal hearing listeners under various masking conditions.

2. Recording FFP from listeners with sensorineural hearing impairment.

Moushegian, Rupert and Stillman (1978) used both methods. In their masking studies, they recorded the FFP to a 500 Hz tone burst at 55 dB nHL and masked with various types of competitive stimuli at 60 dB nHL: wideband noise with high-pass filtering at 1000, 1500, or 2000 Hz to 7000 Hz; or narrow bandpass noise 1000 Hz wide (either 1500 to 2500 Hz, or 2000 to 3000 Hz). They observed that FFPs obtained with high-pass masking noise were essentially the same in latency, amplitude and waveform as the unmasked FFP. The FFP was affected by low-to-mid frequency, narrow band noise. At +15 dB signal-to-noise ratio (SNR), these researchers observed reduced amplitudes of the early waves of the FFP with normal subsequent waves. As the SNR was reduced, the FFP diminished and vanished at 0 to +5 dB SNR. Moushegian et al. (1978) interpreted their data to indicate that the low-frequency narrow band noise effectively masks activity in the apical end of the cochlea.

Huis in't Veld, Osterhammel and Terkildsen (1977) used a 300 Hz wideband of noise centered at the traditional octave frequencies of the audiogram and masked a 10 msec tone burst at 500 Hz. A moderate stimulus level of 83 dB peak equivalent SPL was used to elicit a clear FFP and avoid eliciting middle ear muscle reflexes. Their data revealed

maximum reduction of the FFP when the masking noise was restricted to the low-frequency region. The investigators concluded that the apical portions of the cochlea are responsible for generation of the far-field FFP to a 500 Hz tone burst, at least for signals of moderate SPL.

Davis and Hirsh (1976) reported that a high-pass masking noise delayed the FFP onset about 1.0 msec when the response latency was compared to the latency of the FFP without masking. This latency shift was assumed to represent the contributions of the later-responding apical segment of the cochlear partition. Davis and Hirsh concluded that this evidence supported the concept that, for high level, low-frequency stimuli, FFP is initiated at the basal end of the cochlea in the tone-burst-alone condition, and at the apical end for the tone-burst-plus-high-pass-masking condition.

Gardi and Merzenich (1979) examined the effect of high-pass masking on the FFP in normal hearing human and cat subjects. The latency of the FFP increased systematically as the low-frequency cutoff of the masker decreased. The unmasked latency to a particular response peak in the FFP to an 800 Hz probe tone lengthened 1.5 to 1.8 msec when the FFP was masked with a low-frequency cutoff of 1200 Hz. Amplitudes of the masked FFP, even with a low-frequency cutoff of 2000 Hz, were always less than the unmasked FFP.

In contrast to Gardi and Merzenich's report, Yamada et al. (1979) presented evidence that suggested that there

is an increase in the absolute amplitude of the high-pass masked FFP when compared to the unmasked condition. At a low-frequency cutoff of 1800 Hz, when the probe tone level was at 70 dB normal Hearing Level (nHL), there was a significant enhancement of the FFP amplitude. No such response amplitude increase was reported when lower stimulus SPLs were used. Yamada et al. (1979) also observed that the large decline in FFP amplitude occurred as a function of the low-frequency cutoff of high-pass noise when the masking noise began to mask the apical turn of the cochlea. The response decline was especially apparent at low probe and masker levels.

Clinical Studies

A number of researchers have reported that the FFP can be recorded from patients with moderate-to-severe, high-frequency hearing losses (Stillman, Moushegian and Rupert, 1976; Huis in't Veld et al., 1977; Sohmer et al., 1977; Yamada et al., 1977; Yamada et al., 1978; Moushegian et al., 1978). Moushegian et al. (1978) reported findings from a subject with high-frequency hearing deficit caused by streptomycin poisoning. The FFP was characterized by distinct waveforms with appropriate latencies and amplitudes. This patient's FFP could be masked by low-frequency narrow bandpass masking. A lack of latency shift in these clinical studies, as well as in the masking studies with normal

listeners (Huis in't Veld et al., 1977), conflicts with the data reported by Davis and Hirsh (1976) in normal hearing subjects in which a 1 msec latency-increase occurred when the tone burst was masked with high-pass noise.

Yamada et al. (1978) reported a study of 28 sensori-neural, hearing-impaired subjects who were divided into four categories based on their hearing impairment. These categories were:

1. Moderate, high-frequency loss.
2. Flat, moderate, low-frequency loss with severe, high-frequency loss.
3. Flat, moderate loss across all test frequencies.
4. Moderate, low-frequency loss.

In the three groups of subjects with low-frequency hearing loss, regardless of the hearing sensitivity for higher frequencies, there was a close relation between pure tone threshold for 500 Hz and the threshold for FFP to the 500 Hz tone burst. In the single group with normal low-frequency thresholds and high-frequency hearing impairment, the low-frequency behavioral and FFP results differed by about 40 dB.

The thresholds for FFP in all four groups were very similar, varying between 40 and 60 dB nHL for patients with moderate, low-frequency loss. For normal hearing subjects

as well as patients with only high-frequency loss, the difference between 500 Hz behavioral and FFP thresholds varied between 20 and 40 dB. Yamada et al. (1978) concluded that FFP for a 500 Hz tone burst was initiated from the apical turns of the cochlea.

These same investigators used high-pass masking noise to mask the FFP in the subjects with low-frequency loss. Noise sufficient to mask behavioral thresholds to high-frequency stimuli failed to shift the low-frequency FFP. Both the Yamada et al. (1978) and Moushegian et al. (1978) studies concluded that, for stimuli presented at low SPLs, the evoked FFP represented the responsitivity of the apical region of the cochlea. Davis and Hirsh (1976), Davis (1976) and Yamada et al. (1978) acknowledged that the low SPL FFP is the response of the apical turn, but that the basal end of the cochlea contributes to the FFP at higher stimulus levels.

Non-Simultaneous Masking Studies

Gardi and Merzenich (1979) argued that simultaneous masking studies of the FFP may be difficult to interpret. Physiological studies (Goldstein and Kiang, 1968; Greenwood, Merzenich and Roth, 1976; Smoorenburg et al., 1976) suggest that combination tones very near in frequency to that of the stimulus tone may be generated in the auditory periphery when both a low-frequency probe tone and a high-frequency

masking stimulus are presented simultaneously. The resultant difference tone may affect the bioelectrical response.

Gardi, Bledsoe and Berlin (1979) reported the use of a non-simultaneous masking scheme to study the far-field FFP in guinea pigs and cats. This masking paradigm was derived from Dallos and Cheatham's 1976 study of whole nerve action potential tuning curves. In the Gardi, Bledsoe and Berlin study, the 800 Hz probe tone was gated on for 15 msec and off for 35 msec. A 35 msec masker tone was presented during the interstimulus interval (ISI). The frequency of the masker tone was varied between 300 and 4000 Hz. The rationale for using this repeated-gap masking arrangement was to avoid the effects of the simultaneous presentation of the masker and probe tones.

"Tuning patterns" for the FFP were generated by plotting the ratio of the amplitude of the masked FFP to the unmasked FFP amplitude as a function of the masker frequency. The ratio measure provided a way of comparing tuning patterns across subjects. Gardi, Bledsoe and Berlin systematically varied the probe and masker tone SPLs. They reported that increasing the masker level while the probe level was held constant broadened the low-frequency portion of the tuning pattern. The increasing breadth corresponded with a greater reduction of the FFP amplitude for masker frequencies below the stimulus frequency. When the stimulus level was increased and masker level held constant, the best

masker frequency increased and the entire tuning pattern shifted upwards in frequency with little change in the width of the tuning pattern. When both the probe and masker levels were increased in equal increments (thus maintaining a constant probe-to-masker ratio), the tuning patterns broadened at both the high- and the low-frequency ends of the curve, and the best masker frequency increased.

Gardi, Bledsoe and Berlin concluded that the tuning patterns for the FFP derived from a repeated-gap masking paradigm in guinea pigs and cats supported the results of simultaneous masking studies in the same species. In both species, they demonstrated that the lower SPL low-frequency tone burst generates an FFP that reflects activity in the apical end of the cochlea. As these low-frequency tone bursts increase in SPL, the far-field FFP is generated by excitation of a larger portion of the cochlear partition, with a considerable amount of activity arising from the basal end of the partition.

The nature of far-field FFPs obtained with non-simultaneous masking tones has not been reported for humans. At least one psychophysical procedure uses a non-simultaneous masking paradigm to define the frequency-analyzing powers of the peripheral auditory system. This method, the pulsation threshold procedure, employs a non-simultaneous, repeated-gap masking arrangement which determines the SPL of a

non-simultaneous masker that just begins to interact with the probe tone.

The pulsation threshold level (PTL) is the level of the probe tone at which its character changes from pulsating to continuous (Moore, 1977). Plomp (1976) considers the PTL to be an effective means of assessing the frequency-analyzing capabilities of the auditory periphery since combination tones and beats may be avoided when the technique is used. The PTL does not occur when the masker stimulus does not contain a frequency component close to the probe tone frequency.

Pulsation threshold levels are plotted for a series of competitive non-simultaneous masking stimuli centered at various frequencies above and below the frequency of the probe tone. The array of data points is referred to as a PTL tuning pattern. The peak of the PTL tuning pattern occurs at the masker frequency which matches that of the probe tone. The PTLs for surrounding masker tones cascade to lower sound pressure levels as a function of the absolute difference in frequency between the probe tone and the masker tone. The appearance of a PTL tuning pattern, then, is an abrupt rising and falling function with a maximum at the same frequency and sound pressure level for that of the probe tone. Regarding patterns of excitation of the cochlear partition, Houtgast (1972) considered the PTL to be a manifestation of the minimum level at which the areas of

excitation for the probe tone coincide with the areas of excitation of the masker stimulus.

The repeated gap masking procedure which is used to establish PTLs may provide both psychophysical and electrophysiological tuning patterns which represent the frequency-analyzing powers of the auditory periphery. Thus this non-simultaneous masking procedure may provide a method to study the cochlear initiation sites of the frequency-following potentials to low-frequency tone bursts.

Statement of the Problem

The purpose of this investigation was to determine the cochlear initiation sites of the far-field, frequency following potentials in humans to low-frequency tones. The advantages of a non-simultaneous masking paradigm used in studying FFP function have been reported in subhuman species. The experimental design for this investigation permitted the comparisons of the effects of masking on the amplitude of moderate and high SPL low-frequency probe tones. The necessity for using two probe tone levels became apparent from the review of previous studies in which moderate level probe tones appeared to initiate FFPs from the apical third of the cochlea, while the high SPL probe tones apparently excited the entire cochlear partition, including the basal end. Continuous high-pass masking noise was included in portions of this study to preclude the basal region of the

cochlea and thereby assess the contribution of the apical portion of the cochlea to the low-frequency, frequency following potentials.

Two null hypotheses were formulated for these experiments:

1. There is no difference between the non-simultaneous, tonal-masked, frequency following potential obtained from low-frequency stimuli in the presence and absence of continuous, high-pass masking noise.
2. There is no difference between the non-simultaneous, tonal-masked, frequency following potential obtained from low-frequency stimuli at moderate and high sound pressure levels.

These hypotheses were assessed by testing the significance of differences that occurred between the tuning patterns for the FFP under four conditions: two in which the basal end of the cochlea was permitted to participate in the far-field FFP, and two in which the basal end was precluded from participation by the presence of high-pass masking noise.

METHOD

Subjects

The subjects for this study were eight adults. There were four males and four females, ranging in age from 20.6 to 29.2 years. These subjects had hearing sensitivity, as indicated by a standard air conduction pure tone audiogram, of 15 dB HTL or better at octave intervals from 250 through 8000 Hz, bilaterally. Pure tone audiometric measurements were obtained using clinical audiometers that met or exceeded the American National Standards Institute's specifications for audiometers (ANSI-1970). Acoustic impedance measurements were made for all subjects on available acoustic impedance meters. Only persons with Type A tympanograms, and the presence of normal contralateral acoustic reflex thresholds at 500, 1000, 2000 and 4000 bilaterally were included in this study. Normal contralateral acoustic reflex thresholds for these frequencies were defined as the elicitation of acoustic reflexes using contralateral stimulation within a range of 70 to 100 dB Hearing Threshold Level (HTL) (Jepsen, 1951; Metz, 1952). None of the subjects reported history of ear disease.

Both the pulsation threshold measurements and electrophysiological measurements were made in conventional,

sound-treated, sound-attenuated suites. Subjects reclined on a cot during all measurements except pure tone audiometry. Subjects were seated during standard audiometry. The left ear of each subject served as the experimental ear because of constraints placed on the recording environment by the acoustic stimulus delivery system.

All subjects were tested in four sessions of 150 minutes' duration. Five-minute rest periods were provided each subject every half-hour during the psychophysical portions of these experiments, and ten-minute rest periods were provided every hour during the electrophysiological portions.

Stimulation and Recording

Probe and Masker Tone Bursts

The probe stimulus was a 500 Hz tone burst with a 2.5 msec rise-decay time, and duration of 125 msec. The tonal masker stimulus was set at one of twelve frequencies: 400, 450, 500, 550, 600, 650, 700, 800, 900, 1000, 1500 or 2000 Hz. The rise-decay time and duration of the masker tone were matched to those of the probe tone.

Both the probe and masker tone were calibrated for each session using the slow mode of a Bruel and Kjaer (B & K) portable sound level meter (model 2203) with octave band filter, appropriate 6 cc coupler, and one inch microphone (B & K, model 4144) attached. The amplitudes for the stimuli

are expressed as the sound pressure level for a continuous presentation of each.

A schematic illustration of the stimulation and recording instrumentation is provided in Figure 1. The probe tone burst was produced by a function generator (Heathkit, model IC-1273) and gated on at a fixed phase by an interval timer and electronic switch (Grason-Stadler, models 471 and 829D). The interval timer controlled the signal duration and time between probe stimuli by triggering the electronic switch. The switch controlled the rise-decay time of the probe tone. The masker tone burst was produced by a function generator (Interstate, model F46) gated on at random phase during the second half of the stimulus epoch. Figure 2 illustrates the sequence of the masker-probe stimuli presentation.

The individual outputs for the probe and masker stimuli were routed to separate channels of a power amplifier (Crown, model D60) and to two step attenuators (Hewlett-Packard, 350D). During certain portions of the experiments the second attenuator for the probe and masker stimuli could be controlled by the subject in the test suite. The probe and masker tones were mixed and matched for 10 ohms impedance in a speech audiometer (G-S, model 162) and coupled to a standard earphone receiver (Telephonics, model TDH-39). The harmonic distortion for the probe tone at 100 dB SPL was measured in the acoustic coupler with the B & K sound level meter and

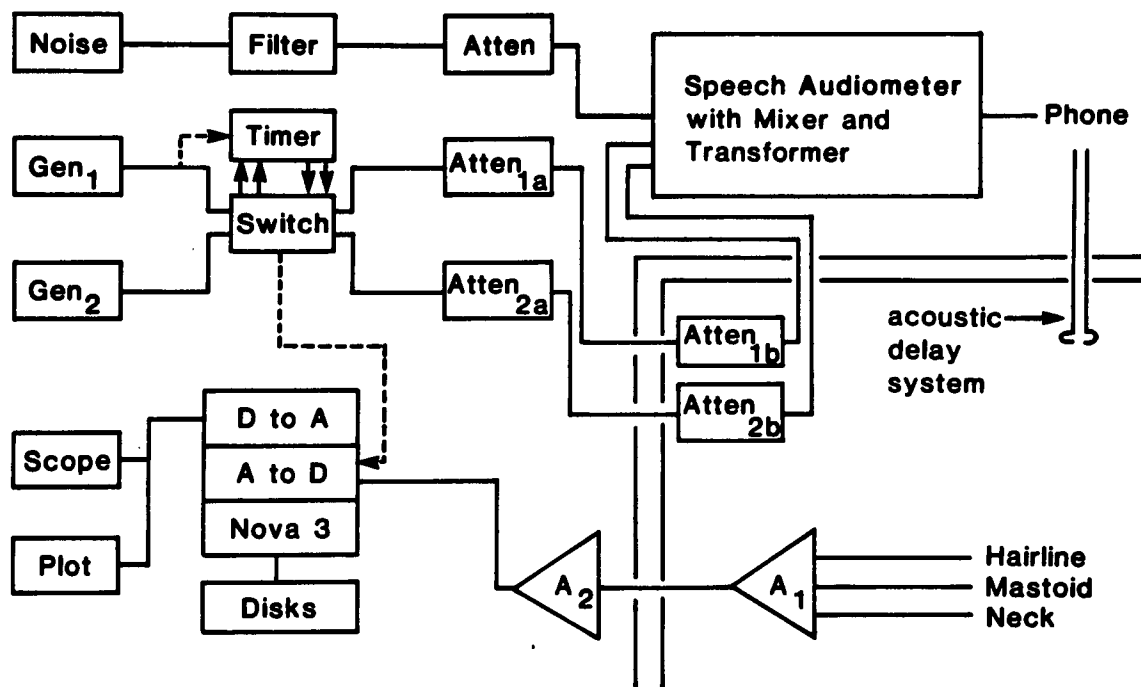


Fig. 1. Schematic of Instrumentation.

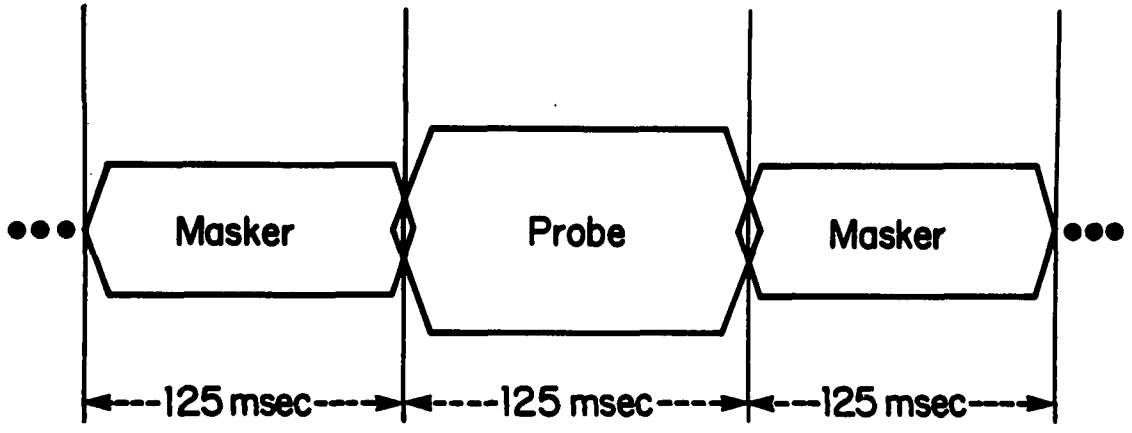


Fig. 2. Sequence of Probe-Masker Presentation.

H-P wave analyzer. The probe signal's second, third and fourth harmonics never exceeded -40 dB re: the probe tone level.

The earphone with cushion (MX-41/AR) was isolated outside the sound suite in a small (7.6 x 10.2 x 14.0 cm) metal box packed with spun fiberglass. A tygon tube, 2.0 meters long (1.3 cm ID, 1.8 cm OD) was attached to the earphone cushion, led through the wall into the sound suite, and terminated in another standard ear cushion fixed to an earphone headband. The earphone isolation was used to reduce the effects of electromagnetic radiation from the receiver and consequent contamination of the electrophysiologic recordings.

High-Pass Masker Noise

A noise generator (G-S, model 4550) produced a wide-band noise that was filtered through two stages of a variable, active high-pass filter (Spencer-Kennedy Labs, model 302) with a low-frequency cutoff at 3000 Hz and a 30 dB/octave roll off. The high-pass noise was coupled to a step attenuator and electrically mixed with the probe and masker tones during certain portions of the experiments. Figure 3 shows the frequency response of the earphone driven by the output of the noise generator and filtered through both the active filter and the acoustic tygon tubing arrangement. The level of the high-pass noise (68 dB SPL) was the highest level that

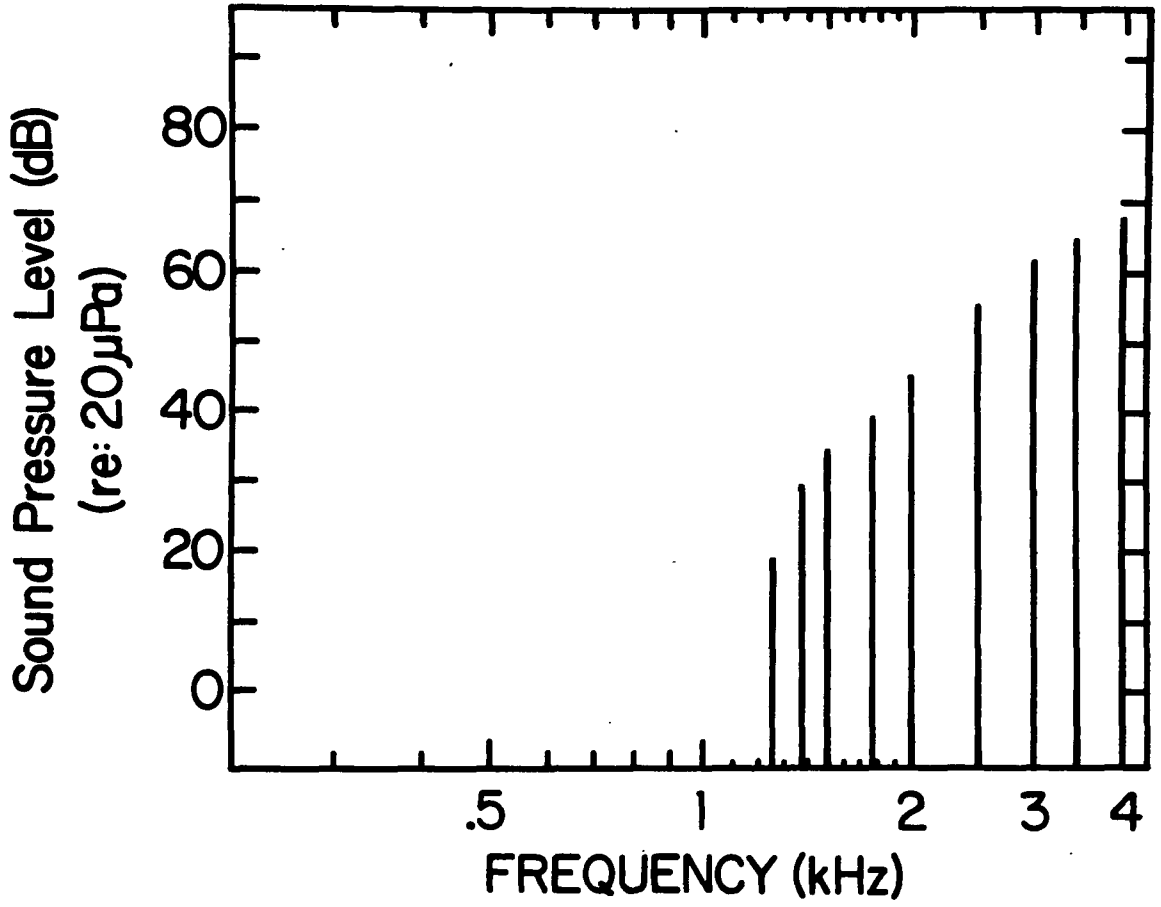


Fig. 3. Frequency Response of High-Pass Filtered Noise.

was insufficient to produce a contralateral acoustic reflex and insufficient to reduce the masked FFP amplitude when compared with the FFP obtained in quiet. These two criteria for determining the level for the high-pass masker noise provided comparable masker levels across subjects for the high-pass noise condition. The use of these criteria precluded the confounding factor of reduction of FFP amplitude by an active acoustic reflex due to the introduction of masking noise.

Subject Preparation

The skin surface was prepared with a vigorous cleaning with an alcohol-soaked gauze pad. Grass EC2 electrode paste was rubbed onto each recording site. Silver disc electrodes were filled with paste, placed on the prepared skin and secured with surgical tape. The impedance between any two electrodes was less than 3000 ohms as determined with an AC ohmmeter specifically designed to measure electrode impedance for auditory evoked potentials (Durrant and Philips, 1979). All inter-electrode impedances were within 33% of each other in order to prevent impedance mismatching at the inputs to the differential amplifier (Geddes and Baker, 1975).

FFP was recorded from the forehead-hairline junction at the sagittal midline, and referenced to two-linked electrodes placed at the neck 10 cm below each mastoid tip.

These two reference electrodes provided a pseudo-midline reference at the base of the skull. The right mastoid, contralateral to the stimulus ear, served as ground. Responses were amplified with a bandpass of 200-3000 Hz by a differential amplifier (Data Inc., model 2124) with a gain of 10,000. Further gain of 100 was provided by an additional amplifier (Burr-Brown, model 3640) for a total gain of 1,000,000.

The amplified signal was coupled to an analog-to-digital converter (ADCV) of a general-purpose computer (Data General, Nova 3). The computer stored the discrete voltages of each EEG sample in 1024 memory addresses with a dwell time of 50 microsec per address. The averager sampling period was 51.2 msec. Averaged FFPs were based on 1024 samples and stored on magnetic diskettes for subsequent analysis.

A synchronized pulse from the interval timer which gated the probe tone was led to an ADCV and triggered the onset of the computer's averager routine. In this manner the averager was a "slave" to the fixed phase onset of the probe tone.

A dual-beam, four trace oscilloscope (Tektronix, type 565) was used to monitor the ongoing EEG activity, as well as the continuously-averaged FFP and the electrical analogs of the masker and probe tones during portions of the recording sessions.

Experimental Procedure

All psychophysical and electrophysiologic measurements made during this investigation were obtained from each of the eight subjects. In this manner, a complete battery of PTLs and FFPs were available for every subject. This repeated-measurements design is considered a natural design "when the supply of subjects is limited relative to the number of treatment combinations to be studied. The precision of this design is potentially far better" than that of the completely randomized factorial designs (Myers, 1972, p. 187).

Pulsation Threshold Levels

The attenuator for the probe tone was set to provide either an 80 or 100 dB SPL (re: 20 μ Pa) probe tone (for the moderate and high SPL conditions, respectively). A masker tone was gated on during the silent periods between each probe tone presentation. Thus, the masker and probe tones each had a 50% duty cycle during the stimulus epoch.

With the probe tone fixed at either the moderate or high SPL, the subject was instructed to adjust the level of the variable masker tone to the highest level at which the masker tone could still be perceived as a continuous tone. This condition was referred to as the pulsation threshold level (PTL). The voltage for the masker tone was measured using the wave analyzer and subsequently converted to SPL

using an artificial ear method of calibration. Five separate estimates of PTL were made for each of the 12 masker frequencies, and for both the probe tone levels. The median value for the five measurements made at each masker frequency-probe tone level condition was determined to be the PTL. The pulsation thresholds also were measured in the presence of a high-pass masker noise.

In all, 48 PTLs were determined for each subject. The order of presentation of 12 masker tones, 2 probe levels, and 2 masking noise conditions, was counterbalanced across subjects. The experimenter-controlled attenuator was randomly adjusted before each measurement to minimize subject bias.

Frequency Following Potentials

FFP Tuning Patterns Without High-Pass Noise. Those stimulus parameters used to establish psychophysical pulsation threshold tuning patterns were used to derive electrophysiological FFP tuning patterns. Specifically, the level for each masker frequency which had established the pulsation threshold for a probe level was used to determine the effects of each masker frequency on the FFP elicited by the probe tone. FFPs were gathered for stimulus conditions that duplicated the 24 PTLs that had been obtained for each subject.

FFP Tuning Patterns With High-Pass Noise. FFPs were obtained from the same repeated-gap masking protocol in the

presence of a continuous high-pass masking noise with a low-frequency cutoff at 3000 Hz.

Unmasked FFP. For each of the four experimental conditions, an averaged FFP response served as a basis for comparison of the amplitude of each of the 12 responses obtained within each of the four conditions.

Analysis

The criterion variable for the electrophysiological experiments was the relative amplitude of the FFP obtained under the various experimental conditions. The method used to measure the FFP amplitude was a planimetric measurement of a representative segment of the FFP record. An epoch of 12.8 msec of each record was cordoned off from the remainder of the record. The epoch began at 5.12 msec after onset of the probe tone. The epochs usually included 5 to 6 maxima and minima each. A straight edge and pen were used to connect each peak to the preceding and following peak and each trough to the surrounding troughs in a similar manner. A compensating polar planimeter (Keuffel & Esser, model 620000) was used to measure the area of the resulting polygon for each record. The measure for each record was compared with the record obtained in the absence of any masker tone. The ratio derived from this comparison was the relative amplitude for the FFP at the respective masker tone.

RESULTS

The purpose of this investigation was to determine the cochlear initiation sites of the human auditory frequency following potential. If the FFP is initiated primarily from the apical portion of the cochlea, then this auditory evoked potential may serve as an index of the sensitivity of low-frequency hearing. To accomplish this purpose, two null hypotheses were formulated:

1. There is no difference between the non-simultaneous, tonal-masked, frequency following potential obtained from low-frequency stimuli in the presence and the absence of continuous, high-pass masking noise.
2. There is no difference between the non-simultaneous, tonal-masked, frequency following potential obtained from low-frequency stimuli at moderate and high sound pressure levels.

Pulsation Threshold Levels

Prior to measuring the FFP from each subject, the pulsation threshold level (PTL) procedure was employed to establish the appropriate levels for the non-simultaneous masker tones. The mean PTLs for the probe tone at 80 dB and 100 dB SPL are illustrated in Figures 4 and 5, respectively.

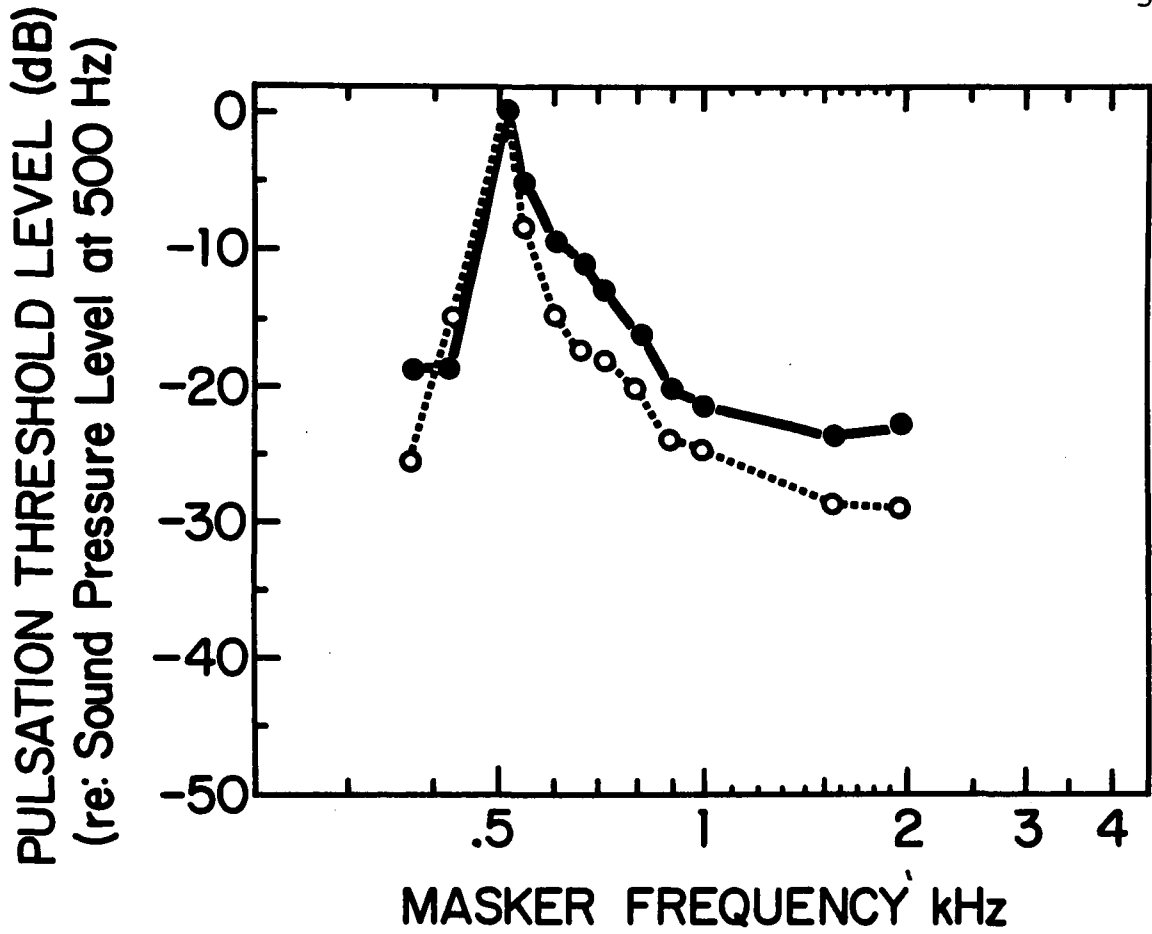


Fig. 4. Pulsation Threshold Level Tuning Patterns for 500 Hz Probe Tone at 80 dB SPL. Tuning Patterns Composed of Mean Values for PTL as a Function of Frequency of Masker Tone. (O)-Probe Tone Presented Without High-Pass Masker. (●) - Probe Tone Presented With High-Pass Masker.

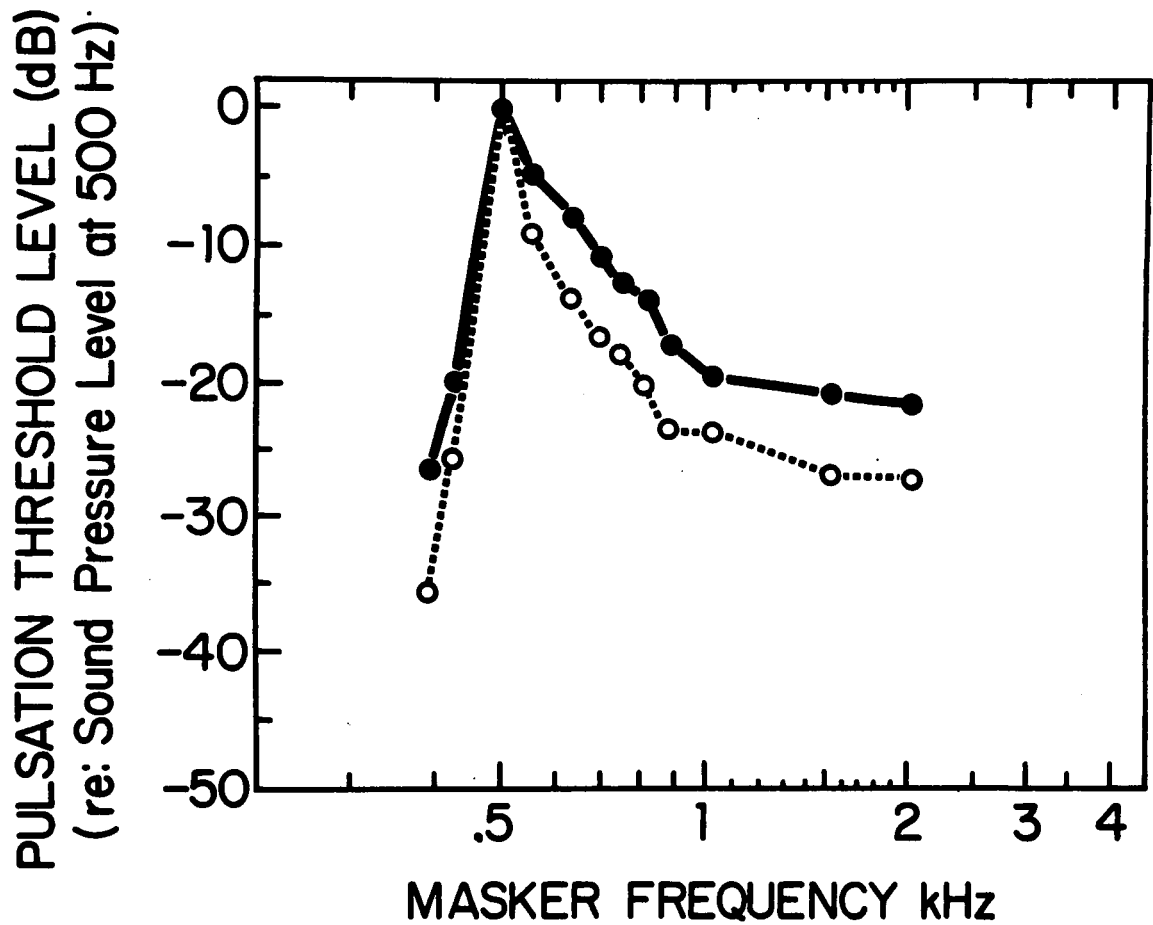


Fig. 5. Pulsation Threshold Tuning Patterns for 500 Hz Probe Tone at 100 dB SPL. Tuning Patterns Composed of Mean Values for PTL as a Function of Frequency of Masker Tone. (○) - Probe Tone Presented Without High-Pass Masker. (●) - Probe Tone Presented With High-Pass Masker.

The mean PTL values for each masker tone are plotted in sound pressure level with reference to the sound pressure of the masker tone at 500 Hz. Examination of the PTL patterns revealed steeply sloping low-frequency portions of the tuning patterns. The peak occurred at the frequency of the probe tone, and the slope was more gradual in the high-frequency "tail" that leveled out between 900 and 1000 Hz.

ANOVA of PTL Tuning Patterns

An analysis of variance was performed to assess the difference between PTL means. The ANOVA for the PTLs is summarized in Table 1. The main effects, probe tone level (PL), high-pass masking (HN) and masking tone frequency (MT) were significant factors in the ANOVA. Interaction effects were not significant factors. Paired comparisons were made between probe tone levels at each masker tone, between high-pass masker conditions at each masker tone, and among masker tones within each probe tone level. The Scheffé Range Tests indicated no significant differences existed between probe tone levels or high-pass masking condition at any masker tone frequency. This post hoc analysis did indicate that significant differences existed:

1. between PTL for 500 Hz, and each PTL at 400, 1500 and 2000 Hz at the 80 dB SPL stimulus level, and
2. between PTL for 500 Hz, and each PTL at 400 and 2000 Hz at the 100 dB SPL stimulus level.

Table 1. Summary of analysis of variance (ANOVA) for pulsation threshold level (PTL). PL = probe level. HN = high-pass noise. MT = masker tone.

<u>Source</u>	<u>Sum of Squares</u>	<u>df</u>	<u>Mean Squares</u>	<u>F-Ratio</u>
PL	9093.12	1	9093.12	86.63***
HN	2293.60	1	2293.60	21.85***
PL x HN	2.48	1	2.48	0.0238
MT	19654.86	11	1786.73	17.02***
PL x MT	872.82	11	79.35	0.7559
HN x MT	399.18	11	36.29	0.3457
PL x HN x MT	162.68	11	14.79	0.1409
S Within Group	35269.92	336	104.97	

*** p 0.001

Effects of High-Pass Masking Noise. The high-pass masking noise produced mean relative PTLs which were elevated in the high-frequency portion of the tuning pattern when compared with the relative PTL means in the absence of continuous high-pass masking. The elevation was in the range of 2 to 8 dB.

Effects of Probe Tone Level. The 100 dB SPL stimulus condition revealed relative PTL means which were lower in the low-frequency portion of the tuning pattern than the relative PTL means in the 80 dB SPL stimulus condition. These diminished relative PTL means resulted in a steeper low-frequency slope in the 100 dB SPL condition.

Frequency-Following Potentials

Examples of the effects of a masker tone set at PTL on the FFP generated by the fixed-phase probe tone are illustrated in Figure 6. The tracing in the top of the left column is the display of the acoustic stimulus. The top right figure is the unmasked FFP. The remaining records in each column are the FFPs obtained during presentation of the masker frequency printed at the left of each tracing. The greatest reduction occurred when the masker tone matched the frequency of the probe tone. For this subject the amplitude of the FFP records of 550, 600, 700, 1500 and 2000 Hz masker tones also appeared attenuated. As a matter of contrast, the amplitude of FFP records for 900 and 1000 Hz were

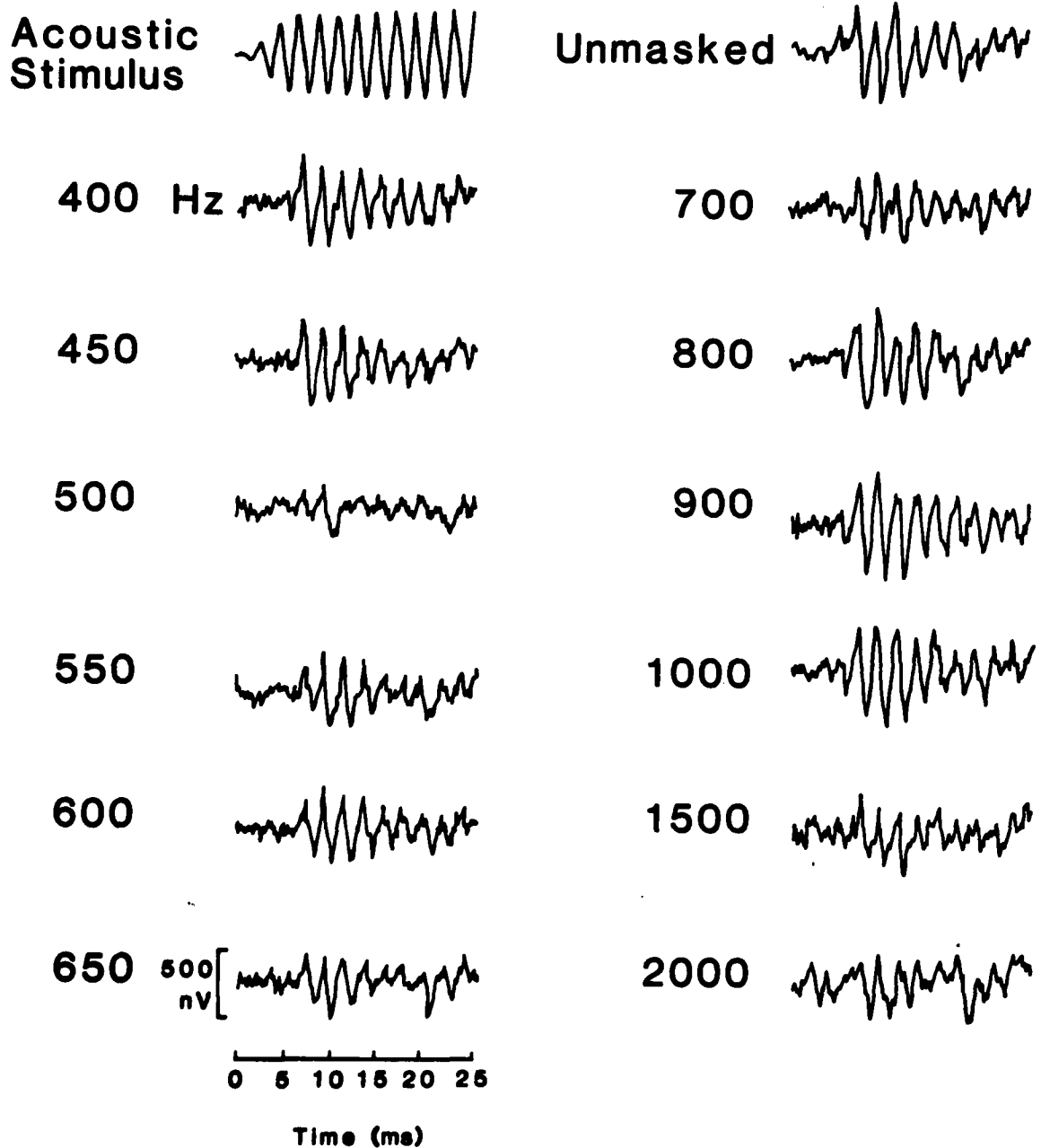


Fig. 6. A Series of Tonal-Masked FFP Responses to a 500 Hz Probe Tone at 80 dB SPL. The Acoustic Stimulus is Shown at the Top of the Left Column. The Unmasked FFP Response is Shown at the Top of the Right Column. The Number at the Left of the Remaining Responses Corresponds to the Frequency of the Masker Tone at Pulsation Threshold Level.

augmented. The reduction in FFP amplitude shown in these tracings was typical of that seen in other subjects.

Configurations of FFP Tuning Patterns

The group means for relative change of FFP amplitude as a function of the masker tone frequency are illustrated in Figures 7 and 8. The scale for the relative amplitude of the FFP has been inverted. The peaks in the derived tuning patterns represent the greatest reduction in FFP amplitude. This manner of displaying the dependent variable was employed to facilitate the comparisons of FFP tuning patterns with the PTL tuning patterns.

FFP Tuning Patterns Without High-Pass Noise. The group means for relative amplitude changes in FFP in the presence of a non-simultaneous masker tone and without high-pass masking noise are illustrated in Figure 7. Several observations were made about the two FFP tuning patterns obtained without the high-pass noise:

1. The greatest FFP amplitude reduction occurred at the frequency of the masker tone which matched the frequency of the probe tone. This occurred for both probe tone levels.
2. There was an appreciable reduction in FFP amplitude for masker tone frequencies above 800 Hz for both probe tone levels. The extended range of masker tone frequencies which appeared to reduce the FFP amplitude is referred to as the secondary areas of

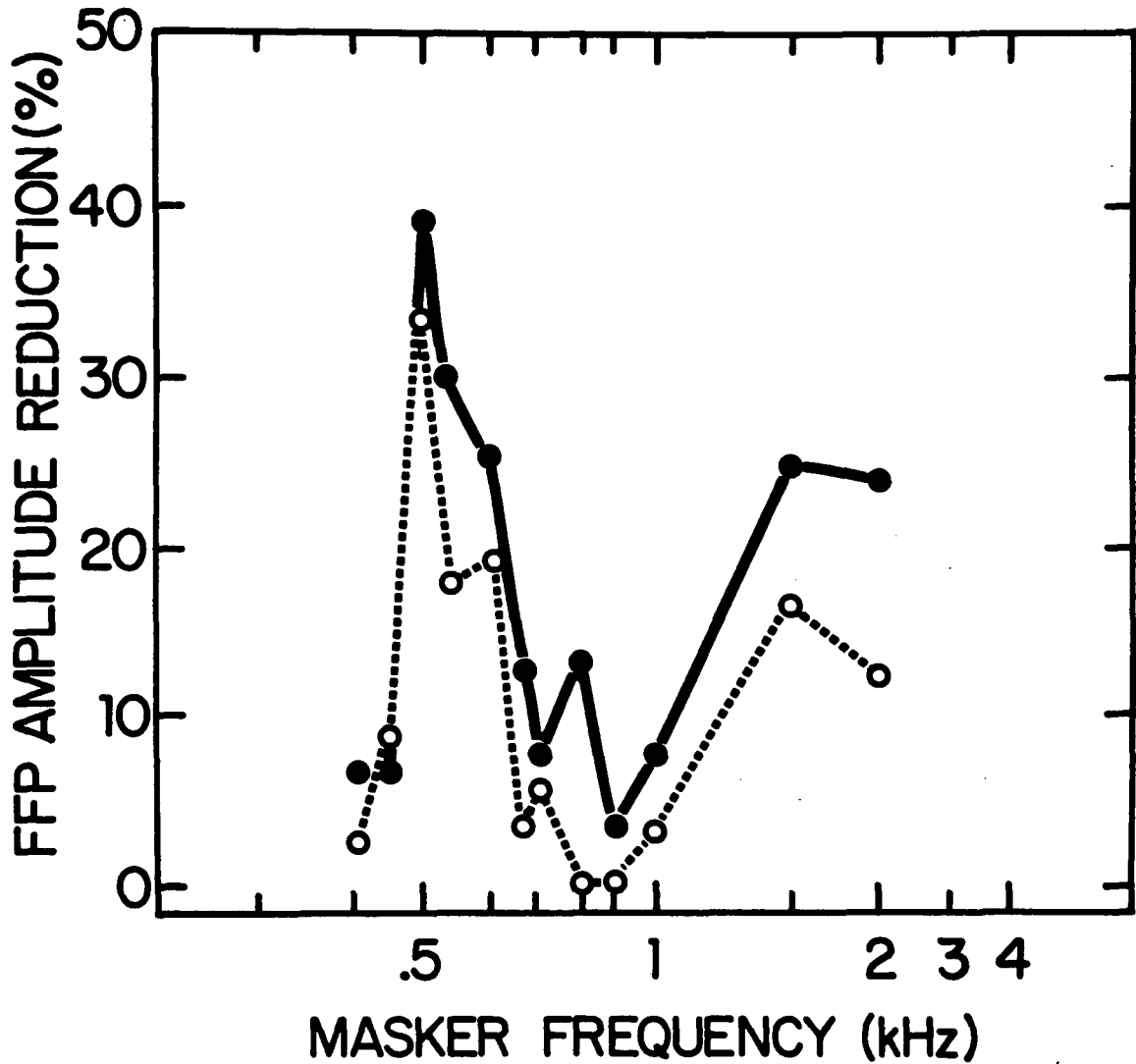


Fig. 7. FFP Amplitude Reduction for a 500 Hz Probe Tone Derived from Non-Simultaneous Masker Tones at Pulsation Threshold Level Obtained Without High-Pass Masking. Data Points are Mean Values for Reduction of FFP Amplitude as a Function of Masker Frequency. Symbols: (○) - Means With Probe at 80 dB SPL. (●) - Means With Probe at 100 dB SPL.

reduced amplitude. The secondary areas of reduced amplitude for the 100 dB SPL stimulus remained at 75% of the unmasked FFP standard amplitude at the highest masker tone frequency (2000 Hz) used in this study.

3. The FFP amplitude reduction was greater for the 100 dB SPL stimulus than for the 80 dB SPL stimulus.

FFP Tuning Patterns With High-Pass Noise. The group means for relative amplitude changes in FFP due to a non-simultaneous masker tone in the presence of a high-pass masking noise are illustrated in Figure 8. Two patterns are displayed: the amplitude change in FFP for the 80 dB SPL stimulus and for the 100 dB SPL stimulus. The following observations were made about the FFP tuning patterns obtained in high-pass noise:

1. FFP amplitude of greatest reduction was at 500 Hz for the 80 dB SPL stimulus and for 500 and 550 Hz for the 100 dB SPL stimulus.
2. The maxima for secondary areas of reduced amplitude occurred when the masker tone frequency was at 1000 Hz. The FFP amplitude reduction when the masker tone was at 1000 Hz for the 100 dB SPL stimulus was essentially the same as the reduction for the masker tone at 500 and 550 Hz.
3. The FFP amplitude reduction was greater for the 100 dB SPL stimulus than for the 80 dB SPL stimulus.

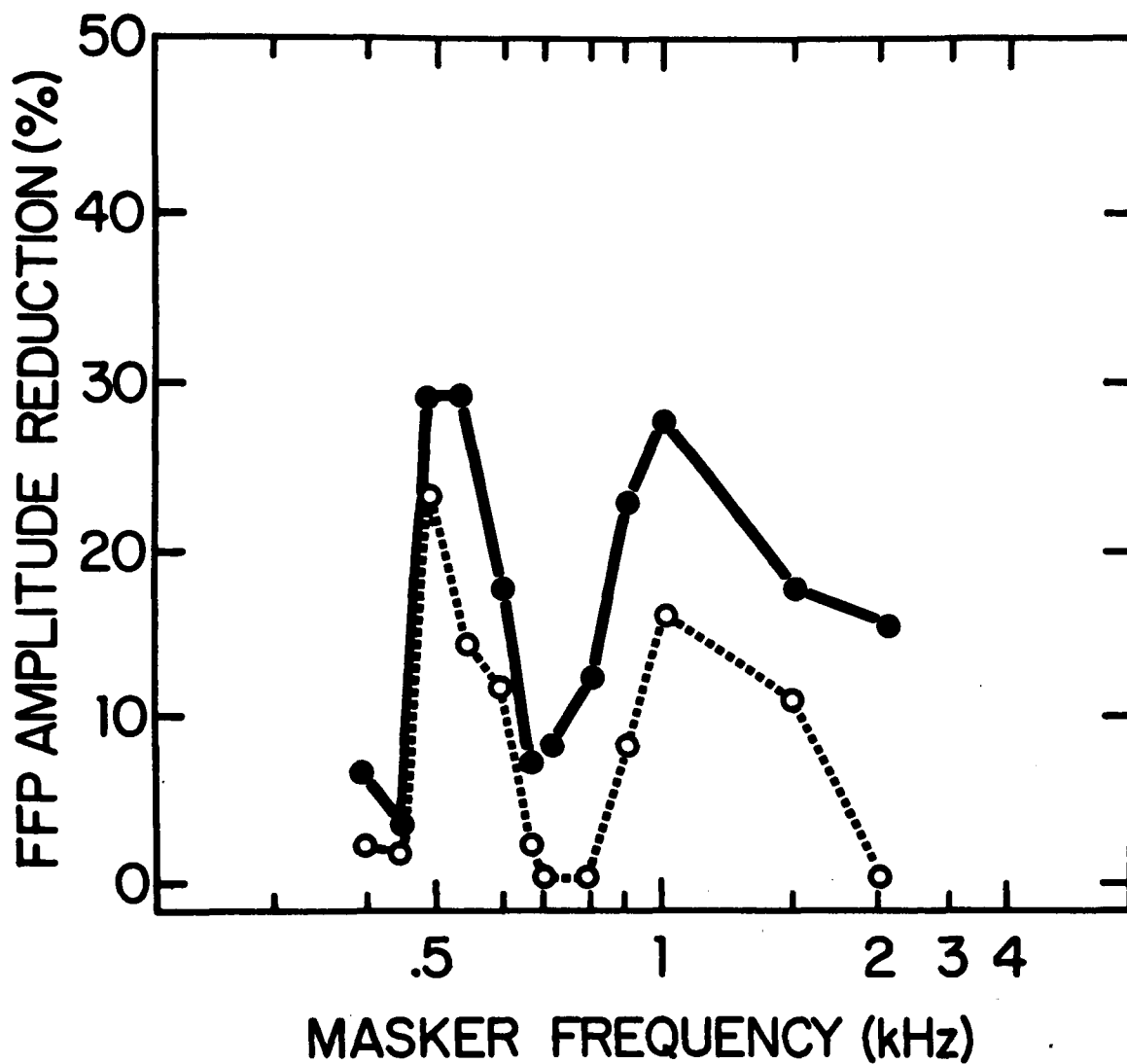


Fig. 8. FFP Amplitude Reduction for a 500 Hz Probe Tone Derived from Non-Simultaneous Masker Tones at Pulsation Threshold Level Obtained in High-Pass Masking. Data Points are Mean Values for Reduction of FFP Amplitude as Function of Masker Frequency. Symbols: (○) - Means With Probe at 80 dB SPL. (●) - Means With Probe at 100 dB SPL.

4. There was no FFP amplitude reduction for the 80 dB SPL stimulus at 2000 Hz masker tone. At the 100 dB SPL stimulus level, the FFP amplitude reduction decreased from 28% at 1000 Hz to 15% at 2000 Hz.

ANOVA of FFP Tuning Patterns

An analysis of variance was performed to assess the effects of the main factors and their interactions. Table 2 presents the summary table for the ANOVA of the FFP amplitude. There were no interaction effects. However, the factors of masker tone frequency (MT) and probe tone level (PL) were significant.

Two post hoc tests were performed for the two significant factors in the ANOVA on relative FFP amplitude. The two mean relative FFP amplitude for each masker tone frequency were compared. None of these comparisons were significant for either the Scheffe or the Newman-Keuls Range Tests.

Based on the results of the ANOVA of the relative FFP amplitude, the first null hypothesis posed for this investigation was not rejected. The high-pass masking noise used in this study did not produce a significant difference in the non-simultaneously tonal-masked FFP.

The second null hypothesis, however, was rejected. That is, the ANOVA results suggested that there is a significant difference between the non-simultaneously tonal-masked FFP obtained at moderate and high sound pressure levels.

Table 2. Summary of analysis of variance (ANOVA) for relative changes in FFP amplitude. PL = probe level. HN = high-pass noise. MT = masker tone.

<u>Source</u>	<u>Sum of Squares</u>	<u>df</u>	<u>Mean Squares</u>	<u>F-Ratio</u>
PL	0.8738	1	0.8738	16.7257***
HN	0.0539	1	0.0539	1.0317
PL x HN	0.0255	1	0.0255	0.4881
MT	2.5420	11	0.2311	4.4236***
PL x MT	0.1852	11	0.0168	0.3223
HN x MT	0.6332	11	0.0576	1.1018
PL x HN x MT	0.3825	11	0.0348	0.6662
S Within Groups	17.5536	336	0.0522	

*** p 0.001

Effects of High-Pass Masking Noise. The group mean data for relative amplitude changes in FFP during presentation of the continuous high-pass masking noise are illustrated in Figure 9. The displayed data represent the FFP means without regard for probe tone level. The two tuning patterns displayed interweave at two masker tone frequencies. The configuration of these patterns reveals:

1. amplitude reduction due to masker tone frequencies 400 to 500 Hz,
2. a rapid increase in relative amplitude to about 800 Hz, and
3. a secondary decrease in relative FFP amplitude, dependent on the presence of high-pass masking.

When the high-pass masker was present, the secondary area of reduced amplitude was in the frequency region above 1000 Hz. Without high-pass masking, the secondary areas of reduced amplitude began at 800 Hz and extended to 1500 Hz. Maximum reduction of FFP amplitude for the high-pass masking condition was abbreviated when compared to the peak of the FFP tuning patterns without the high-pass masking.

Effects of Probe Tone Level. A less-ambiguous pattern of FFP amplitude reduction occurred when the probe level effect was examined. The derived FFP tuning patterns for the 80 dB SPL and 100 dB SPL stimuli are illustrated in Figure 10.

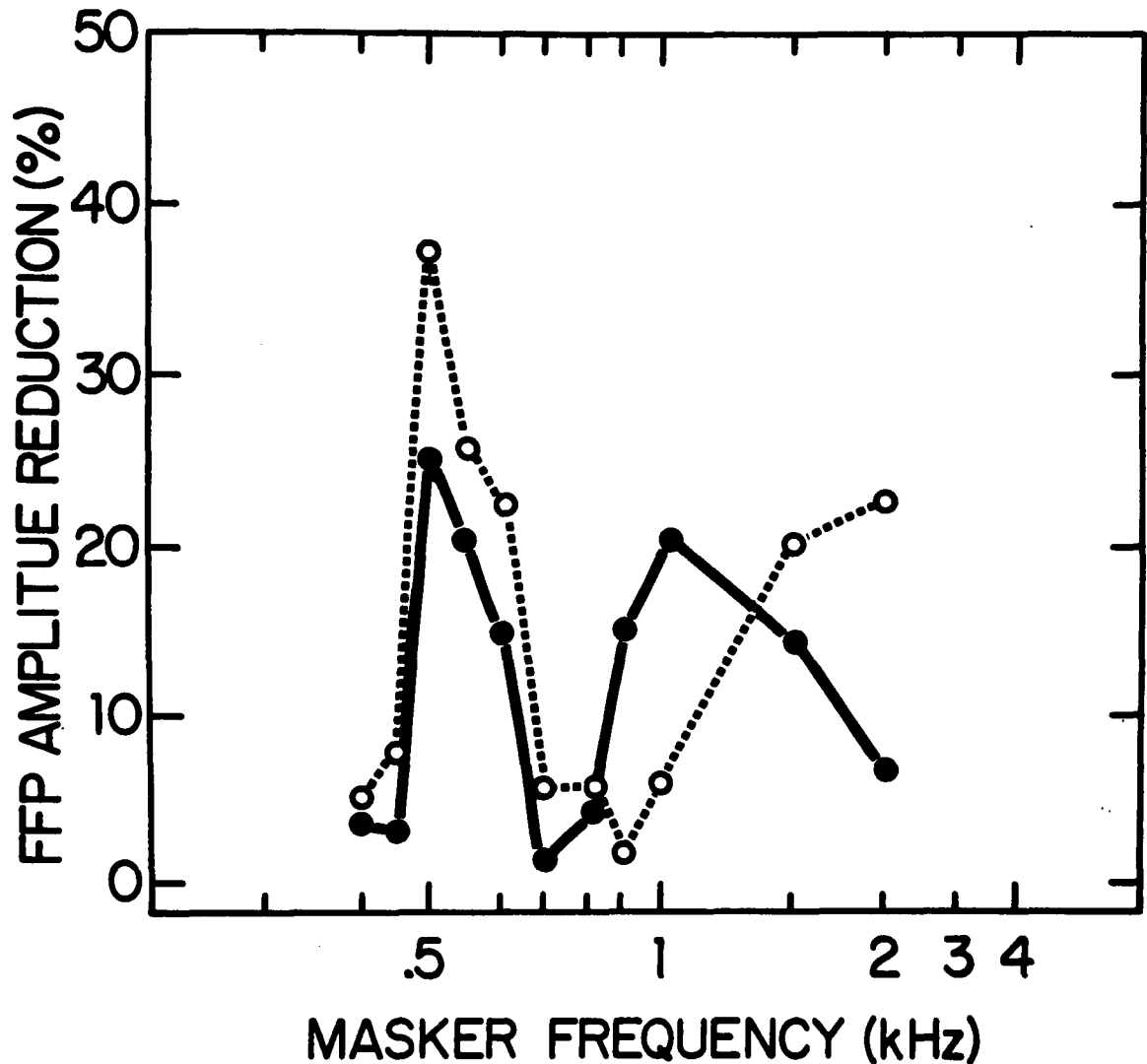


Fig. 9. FFP Amplitude Reduction for a 500 Hz Probe Tone Derived from Non-Simultaneous Masker Tones at Pulsation Threshold Levels. Data Points are Means for Reduction of FFP Amplitude as a Function of Masker Frequency. Means Represent Both Probe Tone Levels. Symbols: (○) - Means With High-Pass Masker. (●) - Means Without High-Pass Masker.

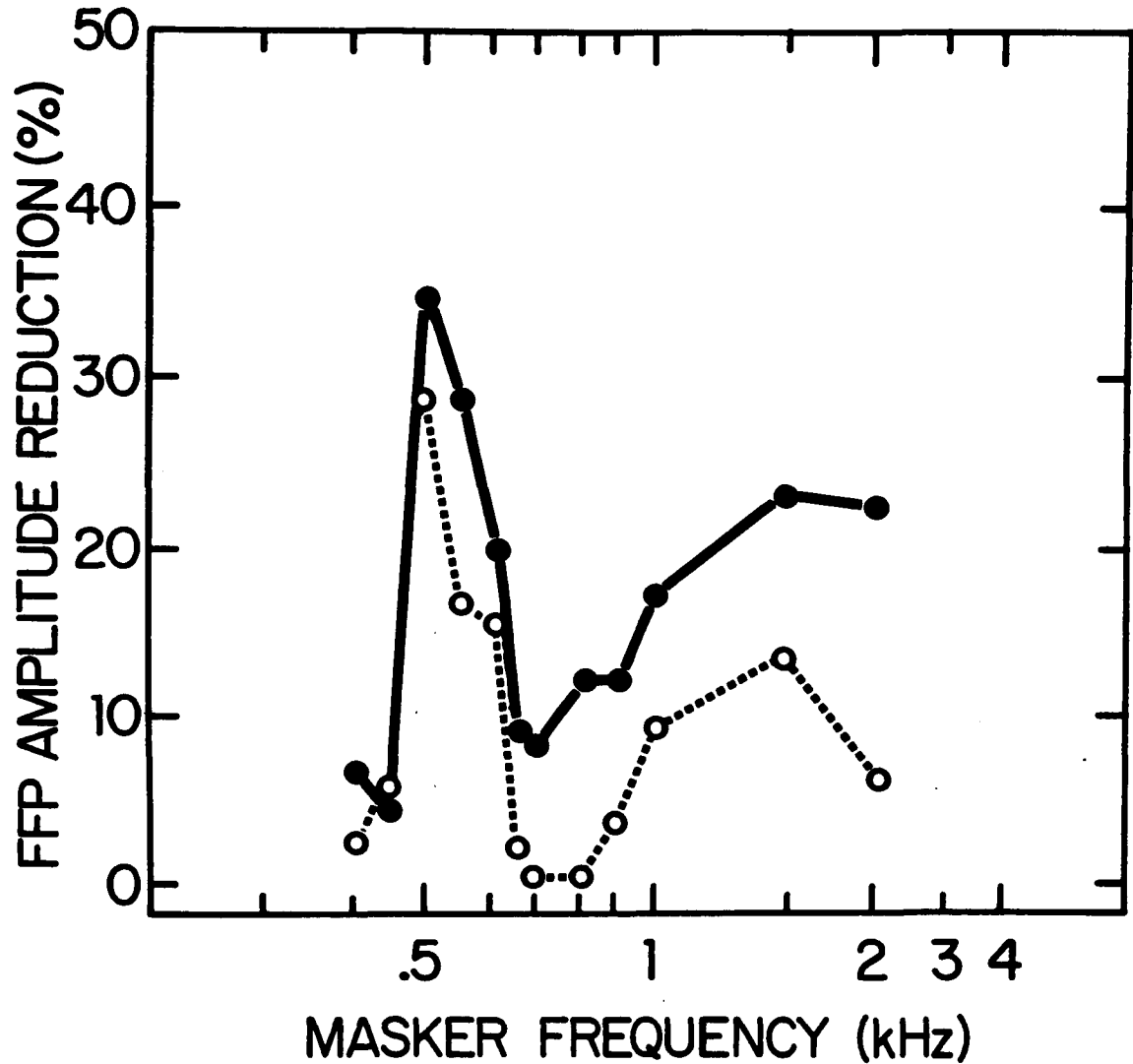


Fig. 10. FFP Amplitude Reduction for a 500 Hz Probe Tone Derived from Non-Simultaneous Masker Tones at Pulsation Threshold Levels. Data Points are Means for Reduction of FFP Amplitude as a Function of Masker Frequency. Means Represent Both High-Pass Masking Conditions. Symbols: (○) - Means for Probe at 80 dB SPL. (●) - Means for Probe at 100 dB SPL.

The displayed data represent the FFP means without regard for the presence of high-pass masking. Both patterns show:

1. a sharp decline in relative FFP amplitude to 500 Hz,
2. an increase in relative amplitude to 700 and 800 Hz
and
3. a slight decrease in FFP amplitude through the remainder of the range of frequencies analyzed.

In the 100 dB SPL stimulus level condition, FFP amplitude remained reduced below the standard unmasked FFP regardless of the frequency of the masker tone observed. The 80 dB SPL stimulus FFP amplitude returned to the standard amplitude in the region of 700 and 1000 Hz.

Secondary areas of reduced amplitude were noted for both levels of the probe tone. For the 80 dB SPL stimulus the area extended from 800 to 2000 Hz. The mean relative amplitude for 2000 Hz in this condition returned nearly to the standard amplitude (96.3%). For the 100 dB SPL stimulus, the secondary area of reduced amplitude extended from 700 to 2000 Hz. The mean relative amplitude for 2000 Hz in the 100 dB SPL stimulus condition, however, remained at 78.0% of the standard amplitude. Since measurements for the competitive masker tone were not made above 2000 Hz, the full range of the secondary areas of reduced amplitude cannot be known for the 100 dB SPL stimulus.

DISCUSSION

Pulsation Threshold Levels

The tuning patterns obtained from the pulsation thresholds for this investigation are comparable qualitatively to previous reports. Houtgast (1973) developed pulsation threshold patterns with one-component maskers for 300, 1000 and 3000 Hz probe tones. The PTL patterns for the 300 Hz probe tone at 70 dB Sensation Level (SL) demonstrated a symmetric function with low-frequency slopes of 60 dB/octave and high-frequency slopes of 50 dB/octave. For the 1000 Hz probe tone at 80 dB SL, the functions were asymmetric with low-frequency and high-frequency slopes in excess of 100 dB/octave and 40 dB/octave, respectively.

In the present investigation, PTL tuning patterns for the 80 dB SPL stimulus yielded low-frequency slopes in excess of 50 dB/octave and high-frequency slopes of 25 dB/octave. For the 100 dB SPL stimulus, the low-frequency and high-frequency slopes were comparable to those for the 80 dB SPL stimulus.

Effects of High-Pass Masking Noise

The group mean PTLs in high-pass noise were consistently higher than the PTLs obtained without high-pass

masking for the high-frequency slope of the tuning pattern. This difference was small, but prevailed throughout the range of masker tones about 500 Hz for both probe tone levels. Statistically the high-pass noise was significant in the ANOVA for the PTL patterns. However, no statistical difference could be achieved for any of the post hoc assessments for any masker frequencies.

These elevated PTLs obtained in continuous high-pass masking noise did not likely reflect the low-frequency cutoff filtering characteristics of the masking noise. The broad band noise was passed with a low-frequency cutoff at 3000 Hz and a 30 dB/octave rolloff. At 1500 Hz, the sound pressure level of the high-pass noise was determined to be 40 dB SPL.

The PTLs may have been elevated by the remote masking of the low-frequency probe tones. Bilger and Hirsh (1956) reported this masking phenomenon in which the thresholds for low-frequency stimuli were raised when a high-pass band of noise was presented at 80 dB SPL or higher. Detherage, Davis and Eldredge (1957, p. 137) explained the physiological reason for remote masking as "an unsymmetrical mechanical action of the inner ear." The SPL for the high-pass noise was lower than those levels reported by Bilger and Hirsh, but still may have been adequate to shift PTLs a few decibels.

Effects of Probe Tone Level

An expected finding with the ANOVA of the PTL was that there was a significant difference between PTLs for the two probe levels. The difference can be attributed to the fact that the PTLs in the ANOVA were scaled in sound pressure level referenced to 20 μ Pa, but, the PTLs were plotted in pulsation threshold level referenced to the SPL which achieved the PTL for the 500 Hz masker tone.

Frequency-Following Potentials

Configurations of FFP Tuning Patterns

FFP tuning patterns derived from the use of non-simultaneous masker tones presented at pulsation threshold levels yielded a bimodal configuration. The primary area of amplitude reduction occurred at 500 Hz. The nature of the pulsation threshold procedure is responsible for the presence of the greatest FFP amplitude reduction at 500 Hz in most of the group data. The average FFP amplitude reduction ranged from 30 to 40% when the frequencies for the probe and the masker tones were matched. It was anticipated that the maximum FFP amplitude reduction would occur when the frequency of the masker matched that of the probe tone. However, the extent of amplitude reduction did not match those seen in subhuman species. Gardi, Bledsoe and Berlin (1979) demonstrated 50 to 80% reduction in FFP amplitude at similar probe and masker levels in non-simultaneous masking experiments.

The sound pressure level for all masker tones, except 500 Hz, was less than the sound pressure level for the 500 Hz probe tone. The contour of the FFP tuning patterns for the masker tones of 450 to 700 Hz, then, qualitatively approximated the contour of the PTL tuning pattern.

The surprising finding in the general contour of the FFP tuning patterns was the secondary area of amplitude reduction. Regardless of probe tone level or presence of high-pass masking noise, the FFP amplitude was reduced for an extended range of frequencies between 800 and 2000 Hz. These amplitude reductions were observed despite the fact that the masker tone was 20 to 30 dB below the sound pressure level for the probe tone. Under some recording conditions, the secondary FFP amplitude reduction equaled that in which the masker tone matched the frequency and level of the probe tone.

Effects of High-Pass Masking Noise

The distinctive features of the FFP tuning patterns obtained with and without the high-pass masking were the change in amplitude reduction at 500 Hz and the area of secondary amplitude reduction. In high-pass noise, the FFP amplitude reduction when the masker tone was 500 Hz was abbreviated. About 26% amplitude reduction occurred in noise, and nearly 40% occurred in the absence of noise. The difference in amplitude reduction at 500 Hz was consistent across both probe tone levels.

The secondary areas of amplitude reduction for the two masking conditions differed in the percentage of maximum reduction and the range of effected frequencies. Without masking, the maximum reduction tended to occur at a higher frequency than with masking. The amplitude of the FFP in noise tended to approach the amplitude level of the standard FFP response as a function of masking frequency. However, the FFP amplitude without noise remained diminished even at 2000 Hz.

The high-pass masking FFP tuning patterns may be thought to reflect the activity of the apical cochlear partition since the high-pass noise masks the basal end of the cochlea. For stimuli sufficiently intense, the entire cochlear partition is free to participate in the initiation of far-field FFP. The unmasked FFP tuning pattern, then, may be referred to as the whole-cochlear partition FFP.

The difference between these FFP tuning patterns may reflect the different areas of the cochlea participating in the FFP generation. Without high-pass masking, the tuning patterns demonstrated that higher frequencies were effective competitive stimuli for the probe tone. The FFP amplitude reduction may even continue beyond 2000 Hz as reflected by the rising slope of the tuning pattern in Figure 9. In addition, the 500 Hz masker tone more effectively competed with the 500 Hz probe tone in the unmasked condition. The tuning patterns at 500 Hz, then, appeared sharper and more

extensive than in the masking condition. In the presence of high-pass masking, the FFP tuning patterns consistently changed shape. The amplitude reduction appeared to be confined to the frequencies below 1000 or 1500 Hz, and practically no FFP amplitude reduction occurred at 2000 Hz.

The morphological changes in FFP tuning patterns and the changes in tone-on-tone AP tuning curves are qualitatively similar. Investigators (Portmann, Aran and Lagourge, 1973; Eggermont, 1977; 1978) have demonstrated a reduction in tone-on-tone AP tuning curves in the noise-exposed ear when compared to the normal ear. The normally-sharp tuning curve tended to flatten out with no clearly-defined tip. Though there is no satisfactory theory which explains the unique predisposition of the basal portion of the cochlea to acoustic trauma, the high-frequency end of the cochlea is subjected to greater structural damage with concomitant high-frequency hearing loss (Durrant, 1978). Thus, both the AP tuning curves in impaired ears and the high-pass masked FFP tuning patterns in normal ears reflect the activity of the apical half of the cochlea. The changes in FFP tuning patterns with the addition of high-pass masking noise support the notion that a considerably large portion of the basal end of the cochlea participates in the far-field FFP to low-frequency stimuli.

Effects of Probe Tone Level

The probe tone level was a significant variable for changes in the FFP amplitude. The peak of the FFP tuning patterns for both probe tone levels was 500 Hz. However, the configuration of the FFP tuning pattern for the 100 dB SPL probe tone reflected more extensive FFP amplitude reduction throughout the entire range of the masker frequencies than did the 80 dB SPL stimulus. The secondary areas of amplitude reduction, especially for the high SPL stimulus, began at 700 Hz and extended through 2000 Hz. The extent of the effects for the high-frequency maskers could not be established. However, the effects could continue above 2000 Hz.

These secondary areas of amplitude reduction may signify that the FFP is initiated from a wide segment of the basilar membrane, including the areas responsive to the 700 through 2000 Hz. The relative contributions of the middle frequencies to the cochlear initiation of the FFP increase with increased probe SPL. A quantitative estimate of the contributions of various areas of the basilar membrane cannot be made from these tuning patterns. Nonetheless, examination of these patterns suggests that the areas outside the narrow segment of the basilar membrane responsive to a 500 Hz tone contribute substantially to the initiation of the FFP to low-frequency, high sound pressure level stimuli.

Implications for Clinical Application of the FFP

The results from the present investigation place strong reservation on the use of the FFP as a clinical assessment for low-frequency hearing. The sound pressure level required to elicit FFP in humans has never been reported less than 40 dB SPL (Glaser, 1976) and is more typically observed at 60 to 70 dB SPL. The levels used in the present study were about 15 and 35 dB SL for normal listeners. The apparent spread of energy for a 500 Hz probe tone at these levels extended at least to 2000 Hz for the high presentation level. In patients presenting a low-frequency hearing deficit and near-normal hearing levels for high-frequencies, the possibilities for under estimation of the hearing loss become apparent.

The use of FFPs for clinical audiology should be limited to the assessment of general cochlear partition function for patients with no apparent response to stimuli used for short-latency ABR, or behavioral assessment. ABR assesses the sensitivity of onset-sensitive neurons which are responsive to high-frequency stimulation. If a patient has residual low-frequency hearing with no response to brain-stem response audiometry, the use of low-frequency, high level stimuli to elicit a general response of the cochlea may prove to be an important addition in the testing of the difficult-to-test patient.

CONCLUSIONS

The results from this investigation support the conclusions made by Davis and Hirsh (1976), Gardi (1978), Gardi, Bledsoe and Berlin (1979), and others:

1. The cochlear initiation sites for the human auditory frequency following potential extend over a large segment of the cochlear partition, and are not restricted to a narrow region of the basilar membrane associated with the responsitivity to a 500 Hz tone.
2. Serious reservations exist for the use of the frequency following potential as an assessment tool for hearing sensitivity for low-frequency stimuli.
3. The use of the frequency following potential to assess the general integrity of the entire cochlear partition, as in the case of patients who are suspected of having profound hearing impairment, may be warranted.

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