To the Graduate Council:

I am submitting herewith a thesis written by Jeffery David Parkinson entitled "Human Frequency-Following Response to Tonal Sweeps in Normal Hearing Subjects." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Arts, with a major in Audiology.

Ananthanarayan Krishnan,
Major Professor

We have read this thesis
and recommend its acceptance:

Accepted for the Council:

Associate Vice Chancellor and
Dean of The Graduate School

# HUMAN FREQUENCY-FOLLOWING RESPONSE TO TONAL SWEEPS IN NORMAL HEARING SUBJECTS

A Thesis
Presented for the
Master of Arts
Degree
The University of Tennessee, Knoxville

Jeffery David Parkinson
May 1997

## Dedication

This thesis is dedicated to my parents

Mr. Weldon M. Parkinson

and

Mrs. Mary A. Parkinson

who gave me room for independence and the confidence to complete any endeavor.

## Acknowledgments

There are many people to whom I am very grateful for their support and contribution to the completion of this thesis. I appreciate the concern and friendship of all the students, faculty, and staff of this department. To my committee, Dr. Ananthanarayan Krishnan, Dr. James Thelin, and Dr. Sam Burchfield, I extend my most sincere thanks for your patience, time, and input. I especially thank my wife, Stefanie Parkinson, for her support, love, and encouragement as well as her patience during the completion of this document. Finally, I thank my God, from whom I draw all strength, and without whom I am nothing.

**Abstract**

Recent studies examining auditory nerve single-unit responses to steady-state and time-variant complex speech-like sounds have implicated neural phase-locking as the basis for the neural encoding of those stimuli. Further, others have shown that the scalp-recorded frequency-following response (FFR) uses the same mechanism to encode steady-state complex sounds at the level of the brainstem. This study proposed to find whether the FFR encodes time-varying sounds at the level of the brainstem. Eight otologically normal subjects listened to tones gliding in frequency from low to high or from high to low. FFRs were recorded from scalp electrodes placed at high forehead (Fpz), left mastoid (A1), and the back of the neck at the seventh cervical vertebra (C7). Characteristics of FFRs to tonal sweeps were consistent with the nature of neural excitation patterns shown in previous studies. The change of frequency in the stimulus and the rate of that change were well preserved in the FFR as indicated by calculated slope values. These results indicate the human FFR is sufficiently dynamic for the encoding of time-varying low frequency stimuli.

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# CHAPTER I

## Introduction

Studies of speech perception have demonstrated that the first two formant frequencies are adequate for vowel recognition (Peterson and Barney, 1952; Brown, 1958; Carlson et al., 1975). Research aimed at describing the neural representation of steady-state vowels in the auditory nerve fibers of animals has implicated neural "phase-locking" as the basis for encoding the spectra of vowels. Specifically, the spectra of vowels are well represented, across an array of fibers, in the distribution of activity locked to the individual harmonics of the stimulus. The fact that subsequent studies have shown that this temporal-place scheme not only encodes steady-state vowels, but also whispered speech (aperiodic) vowels, time-varying consonant-vowel syllables and voice pitch (Miller and Sachs, 1983; Miller and Sachs, 1984; Voight, Sachs and Young, 1982; Young and Sachs, 1979) seem to suggest that phase-locking plays an important role in encoding and signaling the essential features of speech sounds to the central auditory system.

Recent experiments examining the scalp recorded human frequency following response (FFR) have demonstrated that the spectrum of the human FFR contains peaks at frequencies corresponding to the first and second formant frequencies of several steady-state vowels (Ananthanarayan, 1997a, 1997b). Thus, the human FFR, reflecting phase-locked activity in a population of neural elements in the rostral brainstem, does preserve spectral information about complex time-invariant sounds. Given this, it is reasonable to expect the human FFR to preserve spectral information of dynamic time-variant complex sounds.

While the study of neural representation of steady-state vowels has been extensively conducted, it is recognized that the time varying features of speech carry much of the information in speech (Jacobson, Fant, and Hale, 1963). Thus, the primary purpose of this study is to evaluate the nature of the FFR representation of tonal sweeps in normal hearing individuals.

# CHAPTER II

## Review of Literature

Since the purpose of this study is to evaluate the human FFR to tonal sweeps, a review of relevant psychoacoustic and physiologic studies is presented in the following sections.

### Psychoacoustics

Psychoacoustic studies using tonal glides have focused on discrimination of tone bursts and pitch perception. Nabelek and Hirsh (1969) studied the discrimination of tone bursts with differing rates of frequency transition. They found that the ability to discriminate change of frequency depends on the extent of the change from initial to final frequency. They also found that for small frequency changes optimum discrimination occurs for low glide rates and that for large frequency changes optimum discrimination is for high glide rates. Nabelek (1976), reporting on the masking of tone glides, showed that threshold of sensitivity is greater for tonal glides than for constant tones and for faster glides than for slower glides. The implication is that greater masking may occur for the formant transitions of speech than for the more steady state portions of speech. Cohen and Chen (1992) examined the effect of congruous dynamic frequency change among stimulus components on detection of one of those components. They stated that detectability improves when frequency change of signal and masker is not congruous, showing the auditory system is likely able to employ coherent dynamic frequency change among stimulus components. It should be noted that the only similarity between these psychoacoustic studies and the present study is the use of tonal sweeps.

**Physiology**

Results from animal experiments in which responses to steady-state synthetic vowels were recorded from large populations of single unit auditory nerve fibers, have revealed two different schemes of neural representation of vowels. In the first scheme termed the "rate-place" representation formant peaks in the stimulus produce peaks in the discharge rate, across an array of nerve fibers, at frequencies corresponding to the formant frequencies. While this "rate-place" scheme provides a good representation for formant frequencies at stimulus levels below 50 dB SPL it is unstable and fails for stimulus levels greater than 50 dB SPL due to a combination of rate saturation and two-tone suppression (Sachs and Young, 1979).

In the second scheme termed the "temporal-place" or "phase-locking" representation the spectra of vowels are well represented, across an array of fibers, in the distribution of activity phase locked to the individual harmonics of the stimulus. Unlike the "rate-place" scheme, this scheme has been shown to be extremely robust and exhibits a wide dynamic range of intensity (Young and Sachs, 1979). Subsequent studies have shown that the "temporal-place" scheme not only accounts for the encoding of steady-state vowels, but also whispered vowels (Voigt et al., 1982) and time-varying consonant-vowel syllables (Young and Sachs, 1979; Miller and Sachs, 1983).

Directly relevant to the proposed study are the recent findings of Ananthanarayan (1997a, 1997b) who demonstrated that the scalp recorded human FFR carries information about the first two formant frequencies of several steady-state vowels across a range of intensities. These studies would seem to suggest that phase-locking plays an important role in encoding and signaling the essential features of speech sounds, both steady-state and time-variant, to the central auditory system. Thus, the human FFR provides a non-invasive window to evaluate neural encoding of both steady-state and time-variant complex sounds.

## The Frequency-Following Response

### Response Characteristics

The frequency following response (FFR) reflects sustained neural activity in the brainstem phase-locked to the individual cycles of low frequency tones (Moushegian, Rupert and Stillman, 1973; Worden and Marsh, 1978). The characteristics of the FFR vary according to stimulus frequency and intensity (i.e. FFR to 250 and 500 Hz stimuli are observed at lower levels and with greater amplitude than FFR to higher stimulus frequencies). Glaser, Suter, Dasheiff, and Goldberg (1976) observed FFR to stimuli ranging from 70 to 1500 Hz. FFR amplitude increases and latency decreases with increasing stimulus intensity. Estimates of the latency of the FFR have been placed from 5.4 to 7 msec (Gerken, Moushegian, Stillman and Rupert, 1975). Glaser et al. reported the latency of the FFR to be 6 ms for tone bursts at 30 dB SL. They also reported a mean FFR threshold to continuous tones at 40 dB SL, but noted that FFR threshold may be several dB lower for tone bursts. Marsh, Brown and Smith (1975) found a high degree of consistency both within and across subjects in latency, phase, and waveform of averaged FFR.

**Neural Generator(s) of the FFR**

Stillman, Crow and Moushegian (1978) reported the scalp-recorded FFR is composed of several components including a far field recorded cochlear microphonic potential and a low frequency FFR of neural origin. Moller and Jho (1989) found two components of the FFR. One component, equal to the stimulus sinusoid, was isolated through subtraction of responses to tones of opposite polarity. The other component, a slow component with more waveform variability, was isolated by addition of the responses to tones of opposite polarity. Batra, Kuwada, and Maher (1986) used continuous tones to isolate two types of FFR. They reported a neurogenic FFR with a latency of 8.2 msec (+/- 1 msec), consistent with a source at mid-brain, perhaps the inferior colliculus. They also reported an FFR with a shorter latency of 1 msec arising from the cochlea, likely the cochlear microphonic potential.

Moushegian, Rupert, and Stillman (1973) asserted the FFR is of neural origin because: (i)it does not have the frequency range of the cochlear microphonic response; (ii) FFR is absent in the presence of white masking noise; and, (iii) latency of the FFR varies inversely with stimulus frequency. They also reported the FFR is probably from medullary aggregates because FFR latency is about 6 msec. Sohmer and Pratt (1977) added FFR to tone bursts of opposite onset phases resulting in a waveform whose latency equaled about 6 msec and whose amplitude was reduced by white masking noise. Ribaric, Prevec and Kozina (1984) found bone conducted FFR with a latency of about 6 msec in normal hearing subjects and a change in bioelectric activity in profoundly deaf subjects which reproduced the stimulus frequency at a latency of about 6 msec. Peak-to-peak amplitude of responses from both groups were 0.3-1.2 mV.

Glaser et al. (1976) observed FFR latencies in correspondence with ABR waves IV and V. Smith, Marsh and Brown (1975) compared recordings from depth electrodes to those from scalp electrodes. They concluded that at moderate intensities of stimulation, the primary generator of the scalp recorded FFR is the inferior colliculus.

Daly, Roeser, and Moushegian (1976), compared responses to monaural and binaural stimulation in patients with normal hearing and unilateral hearing loss. They concluded the FFR arises from at least two separate symmetric neural sources producing binaural interaction in normal hearing subjects. Ballachanda, Rupert and Moushegian (1994) studied FFR from eight subjects to tone bursts of 500 Hz at three intensity levels. They found asymmetric FFRs at each sensation level, demonstrated by latency and amplitude dissimilarities between ears. They reported these dissimilarities indicate that asymmetries in cortical processing may be reflective of asymmetries in the brainstem. Hink, Kodera, Yamada, Kaga and Suzuki (1980) reported that binaural interaction shows that the FFR reflects binaural processing probably occurring at or below the level of the inferior colliculus. Binaural interaction is a component of the FFR based on the theory that the ears are represented by independent, noninteractive neural populations, therefore, the sum of the monaural left and monaural right response should equal the response to binaural stimulation. Any difference seen in these two values necessarily must be due to an interaction component. The binaural interaction component represents the difference between the summation of the independent monaural responses and the binaural response (Kemp and Robinson 1937; Rosenzwig and Wyers 1955; Wernick and Starr 1968, Dobie and Berlin 1979).

**FFR to Complex Stimuli**

Galbraith and Brown (1990) reported FFR to harmonically complex stimuli were characterized by a clear periodicity at the missing fundamental frequency. Galbraith (1994) revealed that missing fundamental (MF) frequencies were not coded directly in the peripheral neural response as shown by horizontal channel recordings. However, the MF was present in vertical channel recordings, indicating registration of the MF in the brainstem. Greenberg, Marsh, Brown, and Smith (1987) reported that the FFR to the missing fundamental frequency is spectrally similar to that evoked by pure tones equal in frequency to the missing fundamental. Their results indicated that the FFR does indeed reflect neural activity pertinent to the processing of low pitch.

**Representation of Vowels in FFR**

The FFR has been utilized to evaluate the neural representation of synthetic steady-state vowels (Ananthanarayan, 1997a, 1997b). The results of this study indicated that the spectrum of the FFR responses to several different back vowels (/a/, /U/, and /ɔ/ revealed peaks that corresponded to the first two formant frequencies of these vowel stimuli. These formant peaks were robust and identifiable over a range of intensities. Results of this study also indicated that the FFR to these vowel stimuli contained pitch relevant information.

**Rationale**

It is clear from auditory nerve single-unit population studies that neural phase-locking is the primary basis for the neural representation of both steady-state and time-variant complex speech-like sounds. Recently, it has been shown that the scalp recorded human frequency-following response, reflecting phase-locked neural activity in the rostral brainstem, does preserve information about certain spectral features of steady-state back vowels. Given this it is reasonable to postulate that the phase-locked neural activity underlying the FFR generation is sufficiently dynamic to encode time varying features of complex speech-like sounds. Also, it is well recognized that it is the time varying features of speech that carry much of the information. Therefore, in order for this FFR representation to be useful it would have to preserve information about the time varying features of complex sounds. The specific aim of this study is to characterize the human FFR representation of time varying stimuli in normal hearing individuals.

# CHAPTER III

## Methods and Procedures

### Subjects

Eight human subjects ranging in age from 18 to 30 years participated in this experiment. The criteria for inclusion in this group included: (I) hearing sensitivity of 20 dB HL or better for frequencies from 500 to 8000 Hz, bilaterally; (ii) normal appearance of ear canal and pinna; and (iii) normal tympanograms bilaterally. All subjects were unpaid volunteers.

### Stimulus

Frequency-following responses were recorded using four different tone bursts whose frequency was swept linearly, to approximate the formant transitions of speech, over a duration of 80 msec for each stimulus. The tonal sweep stimuli were digitally synthesized and controlled by a signal generation and data acquisition system (Tucker-Davis, System II) interfaced to a microcomputer (Zenith, 486DX, 66 MHZ). The dual-channel stimulus generation module (TDT-DA1) was triggered by pulses delivered by the timing generator module (TDT-TG6). Each output of the dual channel stimulus generators was then routed to a separate programmable attenuator (TDT-HB) before being delivered to the earphones. The timing generator module controlled the timing of the stimuli and provided the synchronous trigger pulse for the onset of digitization. Digital signal generation including control of parameters, such as overall intensity and programming of the research protocol were accomplished by an interactive signal generation and control software (TDT-Siggen). The tonal sweep stimuli were presented monaurally through magnetically shielded TDH-49 earphones encased in Mu-metal. Monaural presentation was chosen based on the precedence established by Ananthanarayan (1997a, b).

**Recording System**

Subjects reclined comfortably in an acoustically shielded room after being instructed to sit quietly and remain still during the recording session. The FFRs were recorded differentially between scalp electrodes placed on the midline of the forehead at the hairline (FpZ)and the 7th cervical vertebra (C7). Another electrode placed on the left mastoid (A1) served as the common ground. The interelectrode impedances were maintained below 3000 ohm. The EEG inputs were amplified by 200,000 and band-pass filtered from 100 to 3000 Hz (6 dB roll-off, RC response characteristics). Each response waveform represented an average of 1500 stimulus presentations over a 100 ms analysis window using a sampling rate of 25 kHz. Responses were repeated once and summed to yield the waveform to be analyzed. Sound levels are expressed as the sound pressure level measured in a 6 cc cavity using a one inch condenser microphone coupled to a sound level meter. Data acquisition was accomplished by the signal averaging and data analysis software (BioSig) of the TDT, System II.

**Response Evaluation**

A joint time-frequency analysis was performed on each of the summed FFR using a joint time-frequency analysis program. This analysis yielded: (I) a three dimensional representation of how the FFR response changes in frequency and amplitude as a function of time; (ii) power spectrum of each instant in time of the FFR waveform; and (iii) magnitude and frequency of the FFR spectral peak as a function of time. The trajectory of frequency change in the FFR over the stimulus duration was then derived from the above information. In order to compare the response characteristics with the stimulus characteristics similar joint time-frequency analysis was performed on the stimuli used in the study. The data analysis portion of the averaging program was used to accomplish response addition, spectral analyses, and printing of waveforms and spectral data.

**Experimental Protocol**

There was one experimental session for each subject.

Subjects first read and signed the informed consent form containing all pertinent information regarding the experiments and their participation in them (see appendix). Pure-tone air-conduction and bone-conduction thresholds, tympanometry and otoscopy was performed at the beginning of the experimental session. The remainder of the session was devoted to data collection. Waveforms were collected for each tonal sweep and for each level.

FFR were obtained under the following experimental conditions:

1) FFR to single frequency sweeps rising or falling in frequency. The parameters of these stimuli were:

    600 Hz sweeping to 400 Hz

    400 Hz sweeping to 600 Hz

    1200 Hz sweeping to 1400 Hz

    1400 Hz sweeping to 1200 Hz

2) Each frequency sweep had a duration of 80 ms.
3) Stimuli were presented monaurally at 60,70,80 and 90 dB SPL.
4) Tonal sweeps were presented at a rate of 6.1/sec using rarefaction polarity.

# CHAPTER IV

# Results

## Responses to 400-600 Hz and 600-400 Hz Sweep Stimuli

### 400-600 Hz Stimulus

Representative FFR waveform data from one subject to the 400-600 Hz tonal sweep is shown as a function of stimulus intensity in Figure 1. This figure shows that the overall amplitude of the response decreases as the intensity of the stimulus is decreased. This amplitude decrement is accompanied by a prolongation of the response latency. Also, at each stimulus intensity the amplitude of the response decreases with time such that the second half of the response is almost unidentifiable as a periodic FFR component. This observation is particularly prominent for the two higher stimulus presentation levels. Finally, the FFR to this stimulus is discernible down to 65 dB.

In order to evaluate the FFRs ability to represent a sweeping tonal stimuli, a joint time-frequency analysis was performed on each of the grand average FFR obtained under each experimental condition. For each stimulus level instant spectra was obtained at 10 msec intervals starting at 10 msec post onset of the stimulus. The spectral data from this analysis is presented for the four intensity levels in Figure 2. Inspection of spectral data across time for each intensity clearly shows that the FFR spectral peak shifts progressively upwards (i.e. to higher

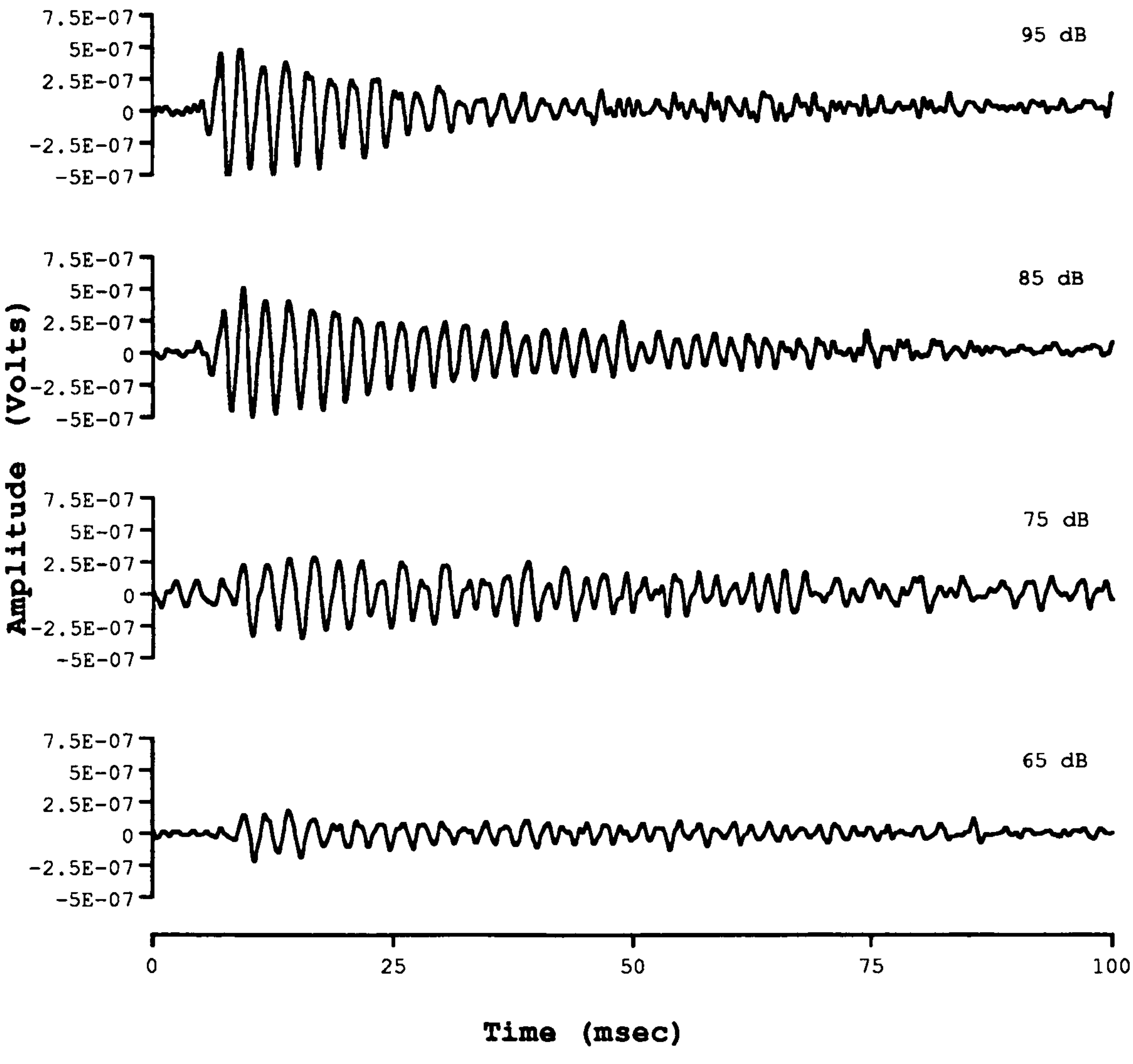


**Figure 1. Representative FFR waveform from one subject to the 400 to 600 Hz tonal sweep stimuli.**

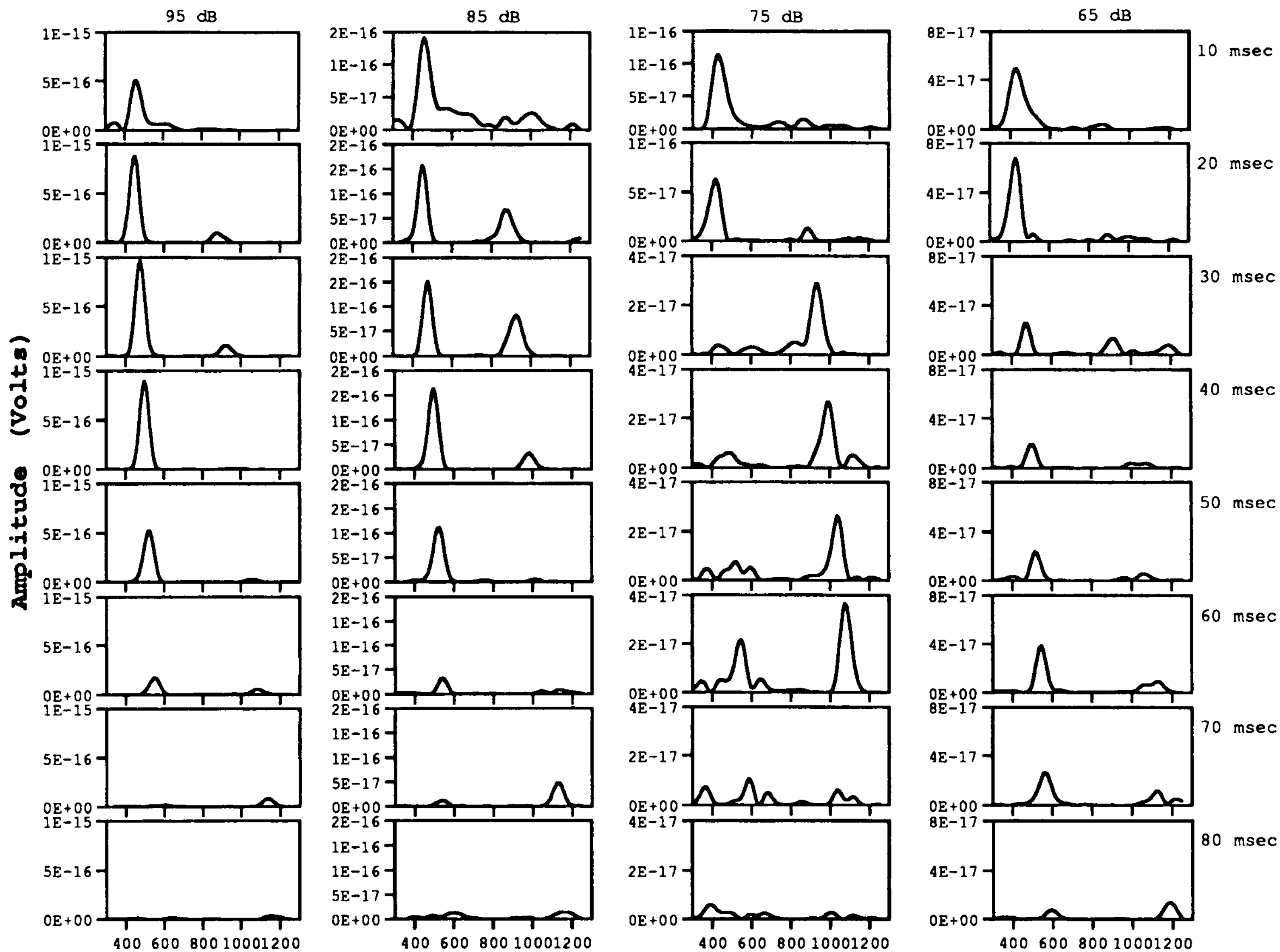


**Figure 2. Spectral data from summed FFR to the 400 to 600 Hz tonal sweep stimuli.**

frequencies) as the tonal stimuli is swept from 400-600 Hz over an 80 msec duration (note changes in amplitude scaling). For each stimulus level response amplitude tends to be more robust for the relatively lower frequencies (associated with the first 40-50 msec of the stimulus) and decreases sharply during the remainder of the stimulus sweep. Also, amplitude of the response, at each instant in time, decreases with decrease in stimulus intensity. A rather unexpected finding is the observation of spectral peaks at the first harmonic of the sweeping stimulus in addition to the peak at the fundamental frequency. Note that the peak at the first harmonic also shows a systematic upward shift in frequency corresponding to the sweeping stimulus. The presence of robust spectral peaks at the higher first harmonic particularly in the absence of peaks at the lower fundamental frequency for the 75 dB SPL condition may be due to rectification within the cochlea.

A more complete characterization of the amplitude change in the FFR during the tonal sweep is plotted in Figure 3 for four intensity levels. In general, this figure shows that the amplitude of the response decreases as a function of time (i.e., amplitude decreases as the frequency increases) at all stimulus levels. The solid lines shown in the figure are fit to data with a simple linear function of the form $y=a+bx$. The non-parallel lines indicate that the slopes of the amplitude change as a function of time are not

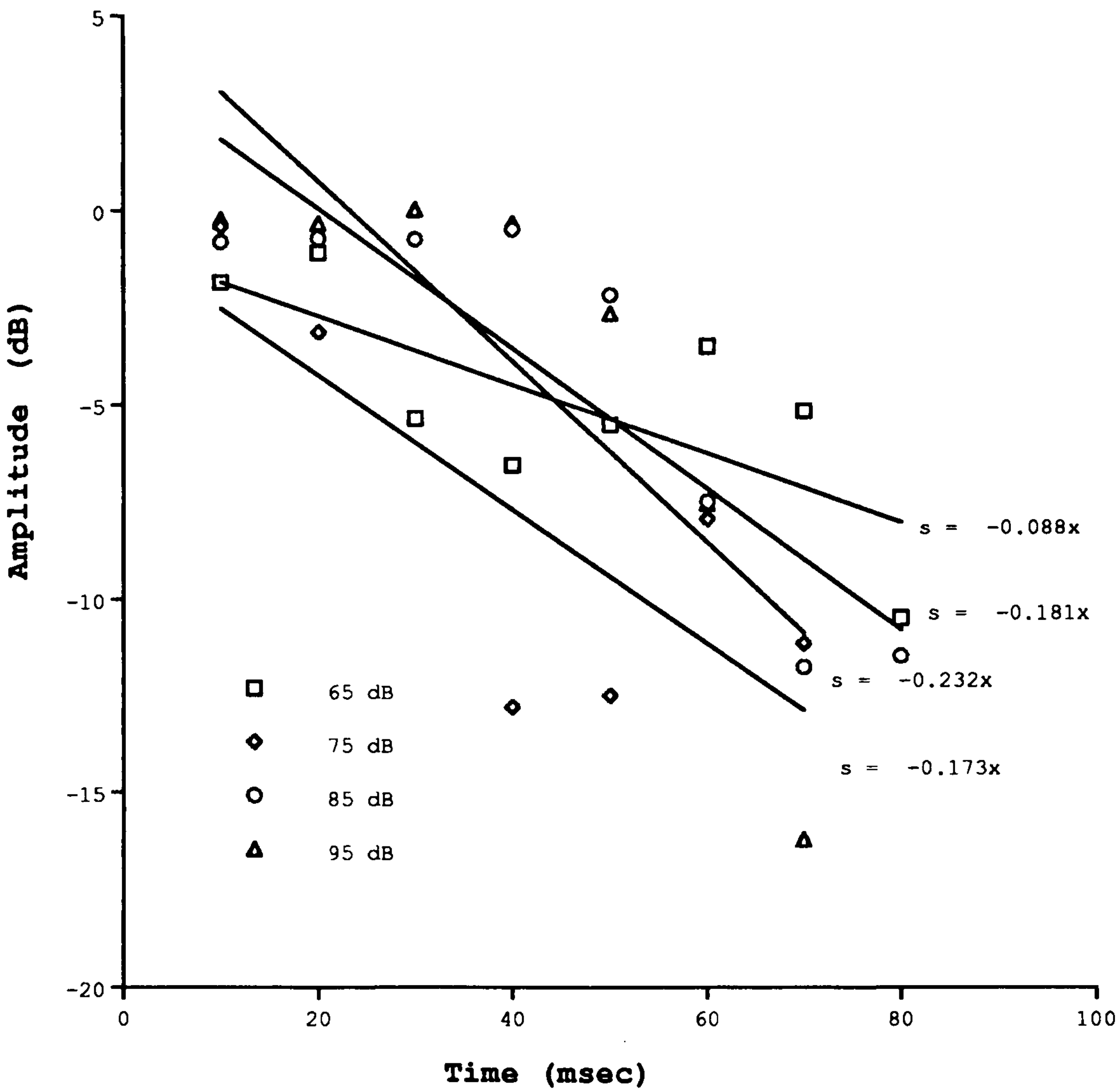


**Figure 3. Mean amplitude of responses to the 400 to 600 Hz tonal sweep stimuli.**

the same across intensity levels. It appears that there is a trend toward steeper slope of amplitude change as the intensity of the stimulus is increased. However, it should be noted that the dramatic amplitude change during the second half of the response contributes in large part to the steeper amplitude slopes observed at the two higher intensities.

The rate of frequency change (with the 10 msec time instant serving as reference) in Hertz, plotted as a function of time for the four stimulus levels, is shown in Figure 4. The results for the 400-600 Hz stimulus is represented by open circles. The data points were well fit by a simple linear function of the form y=a+bx. The essentially parallel functions across levels (also note the similarity in slope values at the four levels) indicate that the rate of change of frequency is independent of the stimulus level. The slope values suggest that the frequency of the FFR is sweeping at a rate of about 2.5 Hz/msec while the slope of the stimulus is 2.4 Hz/msec. This result indicates the FFR well preserves the change of frequency of the stimulus.

**600 to 400 Hz Stimulus**

Representative waveform data from one subject to the 600-400 Hz tonal sweep stimulus are presented in Figure 5. Like the 400-600 Hz waveform data amplitude of the 600-400 Hz FFRs decrease with decreasing intensity with responses

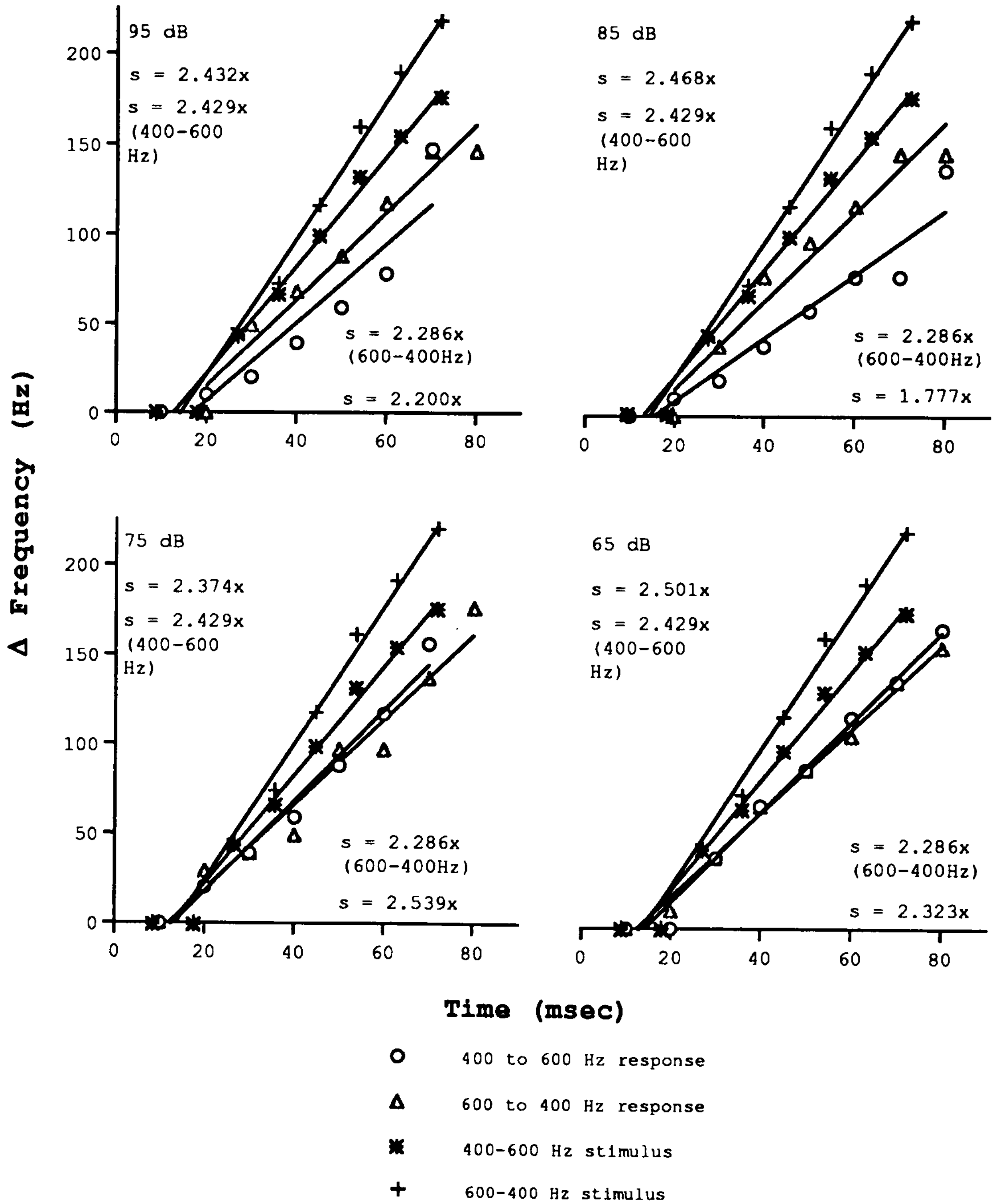


**Figure 4. Change in frequency as a function of time in FFR to the 400 to 600 Hz and 600 to 400 Hz tonal sweep stimuli.**

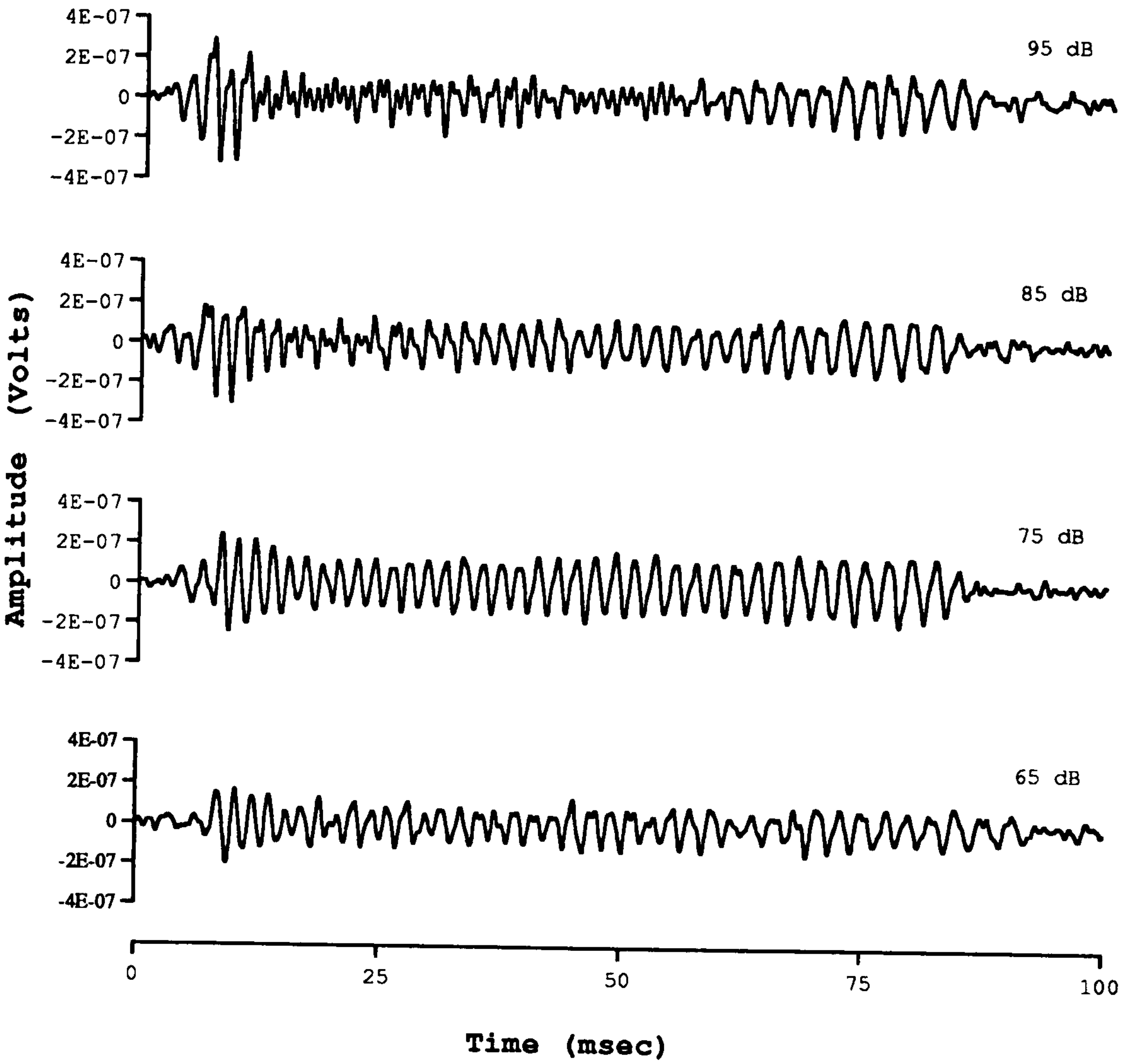


Figure 5. Representative FFR waveform from one subject to the 600 to 400 Hz tonal sweep stimuli.

robust down to 65 dB SPL. However, unlike the 400-600 Hz FFR, responses to the 600-400 Hz stimulus appears to show either a constant amplitude or a gradual increase in amplitude over the 80 msec stimulus sweep. The latency of the response increases with decreasing intensity.

Spectral data for FFR to the 600 to 400 Hz tonal sweep are presented in Figure 6. Examination of spectral data across time for each intensity clearly shows that the FFR spectral peak shifts progressively downwards (i.e. to lower frequencies) as the tonal stimuli is swept from 600-400 Hz over an 80 msec duration. For each stimulus level response amplitude tends to be more robust for the relatively lower frequencies (i.e. for time intervals between 30 and 80 msec). The spectral peaks corresponding to the relatively higher fundamental frequency (during the first 30 msec of the sweep) are smaller in amplitude. Also, the spectral peak at the first harmonic is prominent in this time interval and across levels and shows the systematic downward shift in frequency with time as observed for the fundamental peak. Between time intervals of 30 and 80 msec the spectral peaks (at each instant in time) show a systematic decrease in amplitude as the stimulus level is decreased. Again, the presence of robust spectral peaks at the higher first harmonic particularly in the absence of peaks at the lower fundamental frequency may be due to cochlear rectification.

The amplitude change in the FFR during the tonal sweep

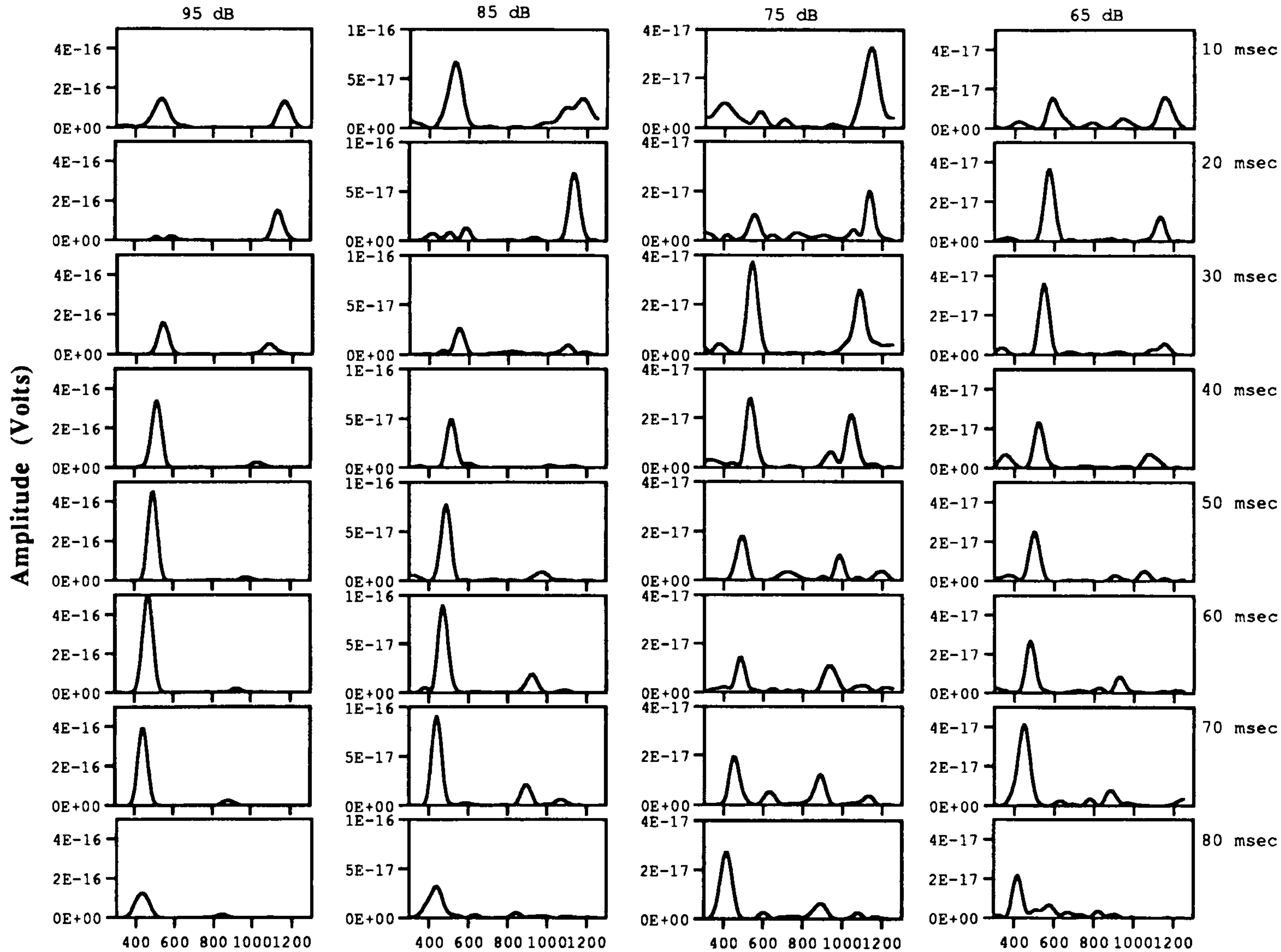


**Figure 6. Spectral data from summed FFR to the 600 to 400 Hz tonal sweep stimuli.**

is plotted in Figure 7 for the four intensity levels. Unlike the data for the 400-600 Hz stimulus, the amplitude of the response increases as a function of time (i.e., amplitude increases as the frequency decreases) at all stimulus levels. The solid lines shown in the figure are fit to data with a simple linear function of the form y=a+bx. The non-parallel lines indicate that the slopes of the amplitude change as a function of time are not the same across intensity levels. It appears that there is a trend toward steeper slope of amplitude change as the intensity of the stimulus is increased.

The rate of frequency change (with the 10 msec time instant serving as reference) in Hertz, plotted as a function of time for the four stimulus levels, is shown in Figure 4. The results for the 600-400 Hz stimulus is represented by open triangles. The data points were well fit by a simple linear function of the form y=a+bx. The essentially parallel functions across levels (also note the similarity in slope values at the four levels) indicate that the rate of change of frequency is independent of the stimulus level. Also, comparison of the data for the 400-600 stimulus and the 600-400 Hz stimulus indicates that the rate of change of frequency in the FFR is essentially identical. The quality of the fit and the slope values suggest that the frequency of the FFR is sweeping linearly at a rate of about 2.3 Hz/msec while the slope of the

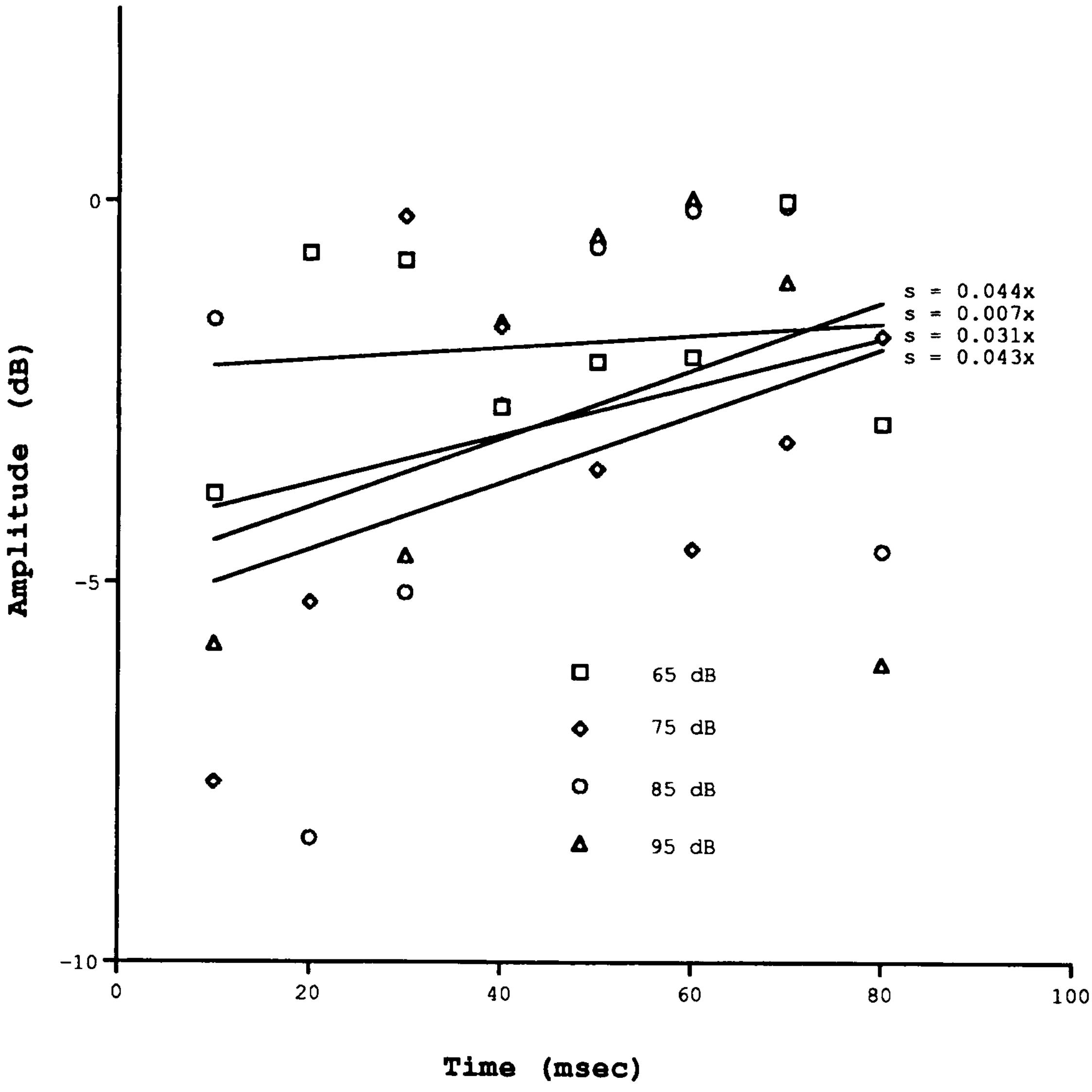


**Figure 7. Mean amplitude of responses to the 600 to 400 tonal sweep stimuli.**

stimulus is 2.3 Hz/msec. It appears the FFR well preserves the frequency change in the stimulus.

**Responses to 1200-1400 Hz and 1400-1200 Hz Sweep Stimuli**

**1200-1400 Hz Stimulus**

Representative FFR waveform data from one subject to the 1200-1400 Hz tonal sweep is shown as a function of stimulus intensity in Figure 8. It is apparent that the responses to this stimulus were less robust than those to the lower frequency stimuli (note the amplitude scale). While the response at the higher intensities appear to show components without measurable latency the onset component of the FFR does show a systematic prolongation of the latency as intensity is decreased. The amplitude reduction with decrease in intensity appears to be more dramatic than that observed for the lower frequency stimuli. Change in amplitude over the duration of the sweep is not readily apparent in the waveform data. It should be noted that for the higher stimulus intensities there was no latency shift in the FFR waveform. Periodicity representing the presence of an FFR component is not apparent at 65 dB SPL.

The spectral data for the 1200-1400 Hz stimulus is shown in Figure 9. Inspection of the spectral data across time for each intensity clearly shows that the FFR spectral peak shifts progressively upwards (i.e. to higher frequencies) as the tonal stimuli is swept from 1200-1400 Hz over an 80 msec duration. For stimulus levels of 85 and 95

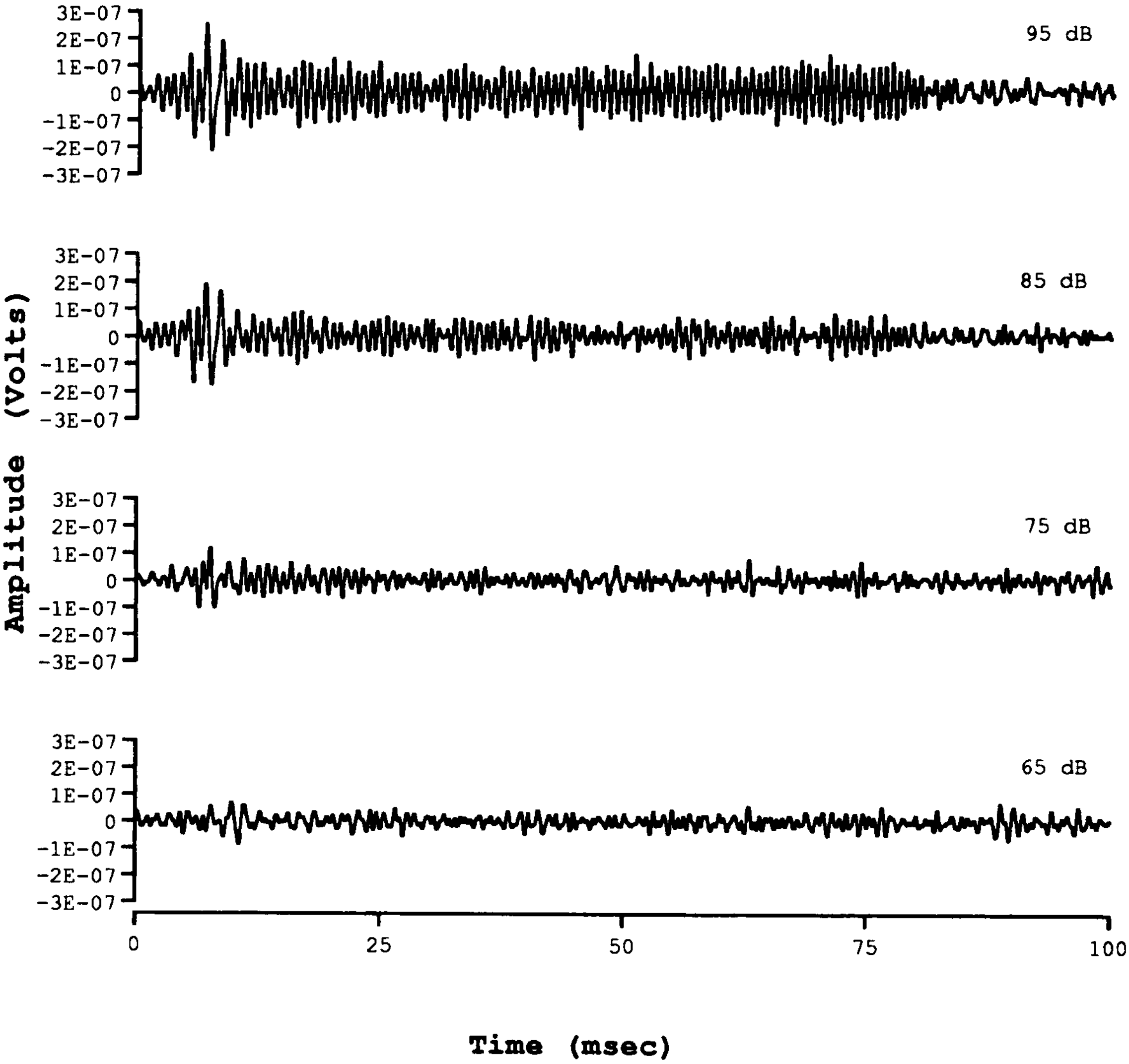


**Figure 8.** Representative FFR waveform from one subject to the 1200 to 1400 Hz tonal sweep stimuli.

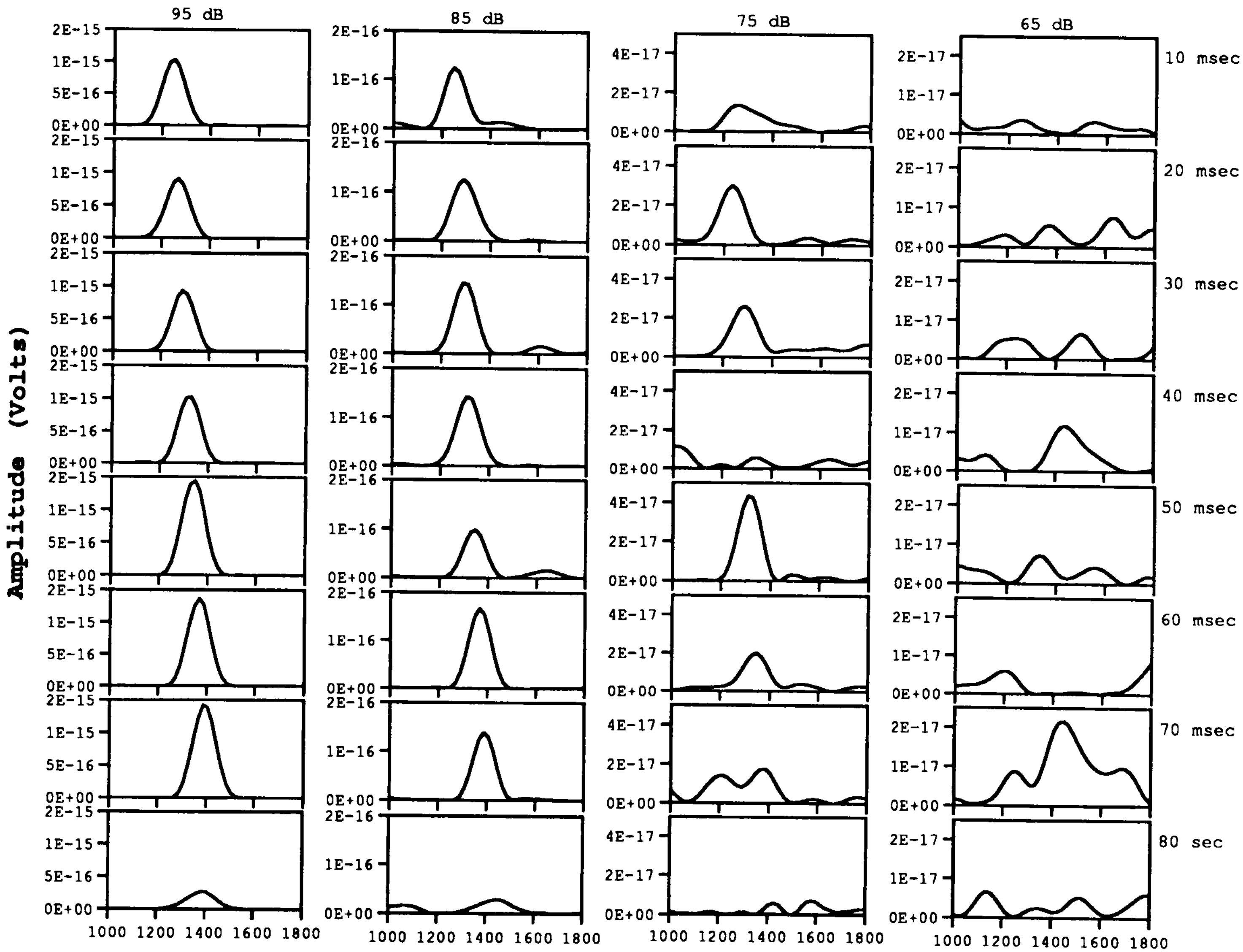


**Figure 9. Spectral data from summed FFR to the 1200 to 1400 Hz tonal sweep stimuli.**

dB SPL response amplitude tends to be robust across all instants in time with amplitude being slightly greater for the 50 to 70 time interval. The amplitude change as a function of time at 75 dB SPL is less systematic and may be characterized as non-monotonic. Consistent with the waveform data no systematically shifting spectral peak was observed for the 65 dB SPL condition. Finally, amplitude of the response, at each instant in time, decreases with decrease in stimulus intensity. Unlike the responses for the lower frequency stimuli, no spectral peaks were observed at any level or time at the harmonic of the fundamental frequency of the 1200-1400 Hz sweeping stimulus.

The amplitude of the FFR components during the tonal sweep is plotted in Figure 10 for the four intensity levels. In general, this figure shows that the amplitude of the response decreases as a function of time (i.e., amplitude decreases as the frequency increases) at all stimulus levels. Recall that no responses were detected for the 65 dB SPL condition. The solid lines shown in the figure are fit to data with a simple linear function of the form $y=a+bx$. The non-parallel lines indicate that the slopes of the amplitude change as a function of time are not the same across intensity levels. It appears that there is a trend toward steeper slope of amplitude change as the intensity of the stimulus is increased. However, it should be noted that the dramatic amplitude change during the second half of the

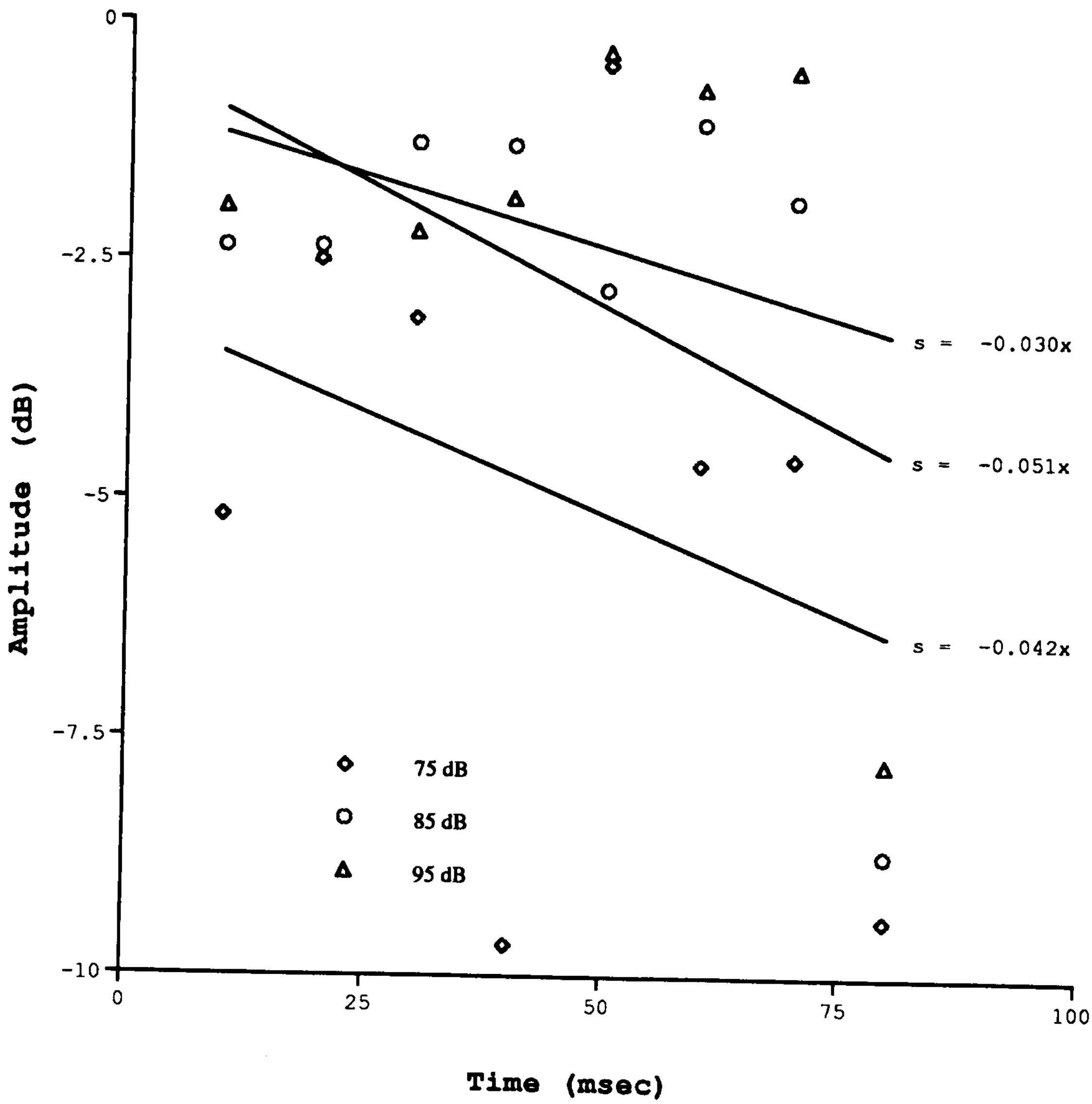


Figure 10. Mean amplitude of responses to the 1200 to 1400 Hz tonal sweep stimuli.

stimulus sweep contributes in large part to the steeper amplitude slopes observed at the two higher intensities. Also, note that the amplitude change over time as indicated by the data points is non-monotonic, particularly for the 75 dB SPL condition.

The rate of frequency change (with the 10 msec time instant serving as reference) in Hertz, plotted as a function of time for the four stimulus levels, is shown in Figure 11. The results for the 1200-1400 Hz stimulus is represented by open squares. The data points were well fit by a simple linear function of the form y=a+bx. Unlike the lower frequency stimuli, the non-parallel functions across levels (also note the differences in slope values at the four levels) indicate that the rate of change of frequency is dependent of the stimulus level. The slope values suggest that the rate of frequency change is greater at 85 and 95 dB SPL compared to the rate of frequency change at 75 dB SPL. The average rate of change across the three levels is about 1.86 Hz/msec, while the slope of the stimulus is about 2.6 Hz/msec. This response slope value is less than that observed for the lower frequency stimuli, and indicates the phase-locking ability is not as strong for this stimulus.

**1400-1200 Hz stimulus**

Representative waveform data from one subject to the 1400-1200 Hz tonal sweep stimulus are presented in Figure

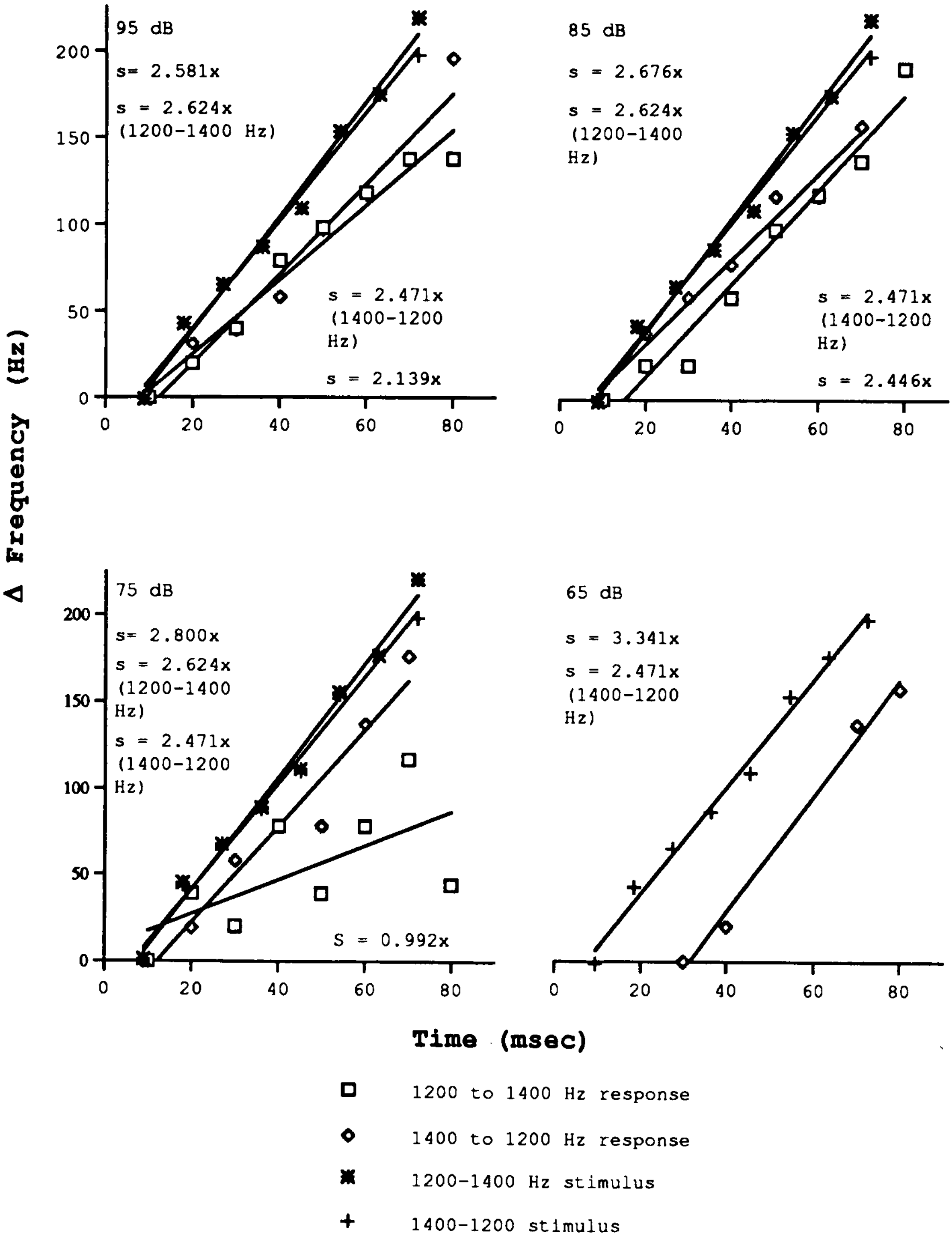


**Figure 11. Change in frequency as a function of time for FFR to the 1200 to 1400 Hz and 1400 to 1200 Hz tonal sweep stimuli.**

12. The decrease in amplitude accompanied by latency prolongation with decreasing intensity is readily apparent. Unlike the 1200-1400 Hz response, identifiable periodic FFR components are visible at 65 dB SPL. Like the 1200-1400 Hz FFR, the amplitude of 1400-1200 Hz FFR shows little or no reduction in amplitude over the duration of the sweep.

Spectral data for FFR to the 1400-1200 Hz tonal sweep are presented in Figure 13. Examination of spectral data across time for each intensity clearly shows that the FFR spectral peak shifts progressively downwards (i.e. to lower frequencies) as the tonal stimuli is swept from 1400-1200 Hz over an 80 msec duration. For each stimulus level response amplitude tends to be more robust for the relatively higher frequencies (i.e. for time intervals between 10 and 30 msec). The amplitude of the response at all levels decreases systematically through the remainder of the sweep. Unlike the 1200-1400 Hz stimulus, clear response peaks were observed for this stimulus even at 65 dB SPL. Again, there were no spectral peaks at the harmonic of the sweeping 1400-1200 Hz stimulus.

The amplitude change in the FFR during the tonal sweep is plotted in Figure 14 for the four intensity levels. Like the 1200-1400 Hz data, the amplitude of the response decreases as a function of time (i.e., amplitude decreases as the frequency decreases) at all stimulus levels. The solid lines shown in the figure are fit to data with a

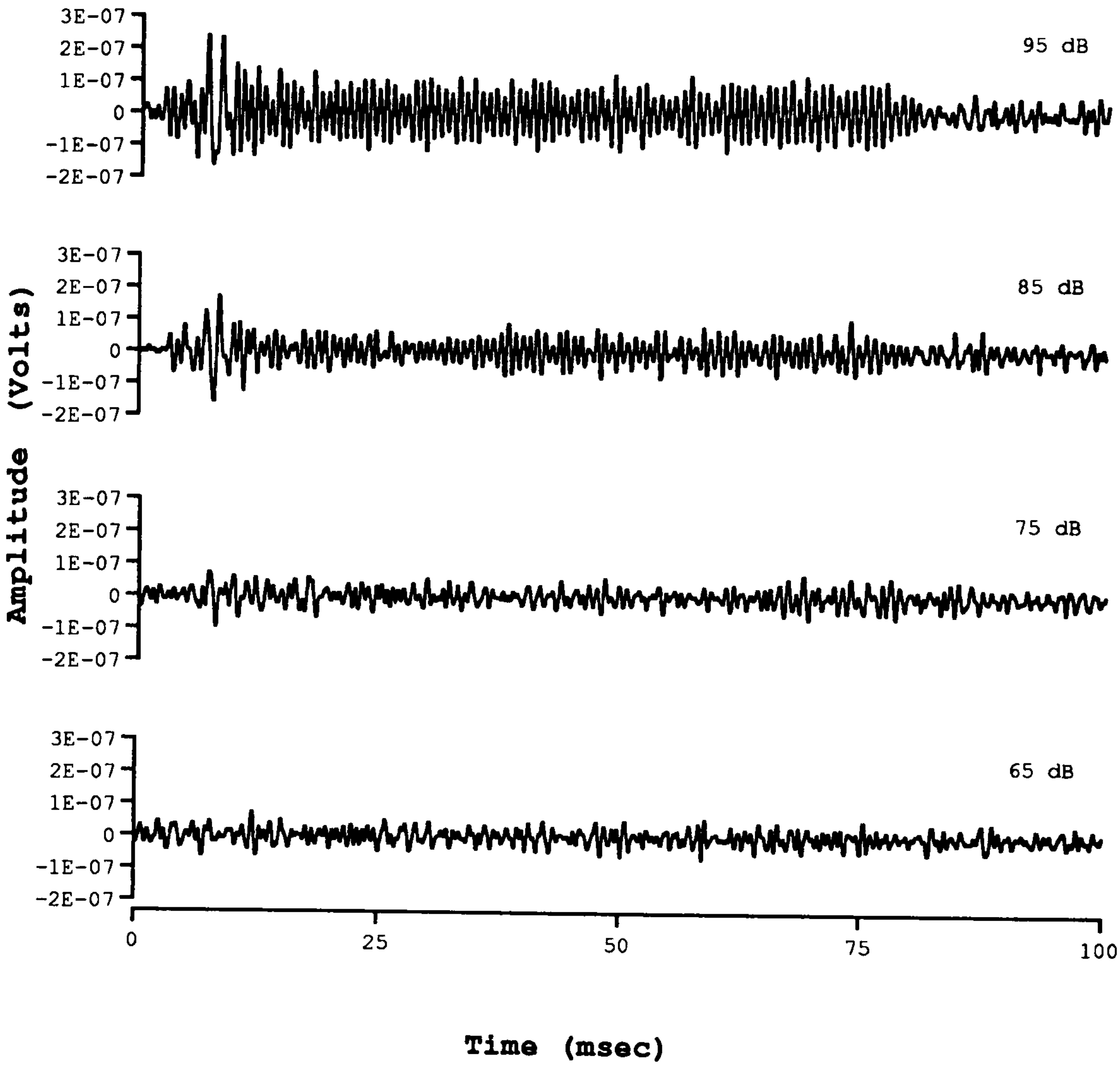


**Figure 12.** Representative FFR waveform from one subject to the 1400 to 1200 Hz tonal sweep stimuli.

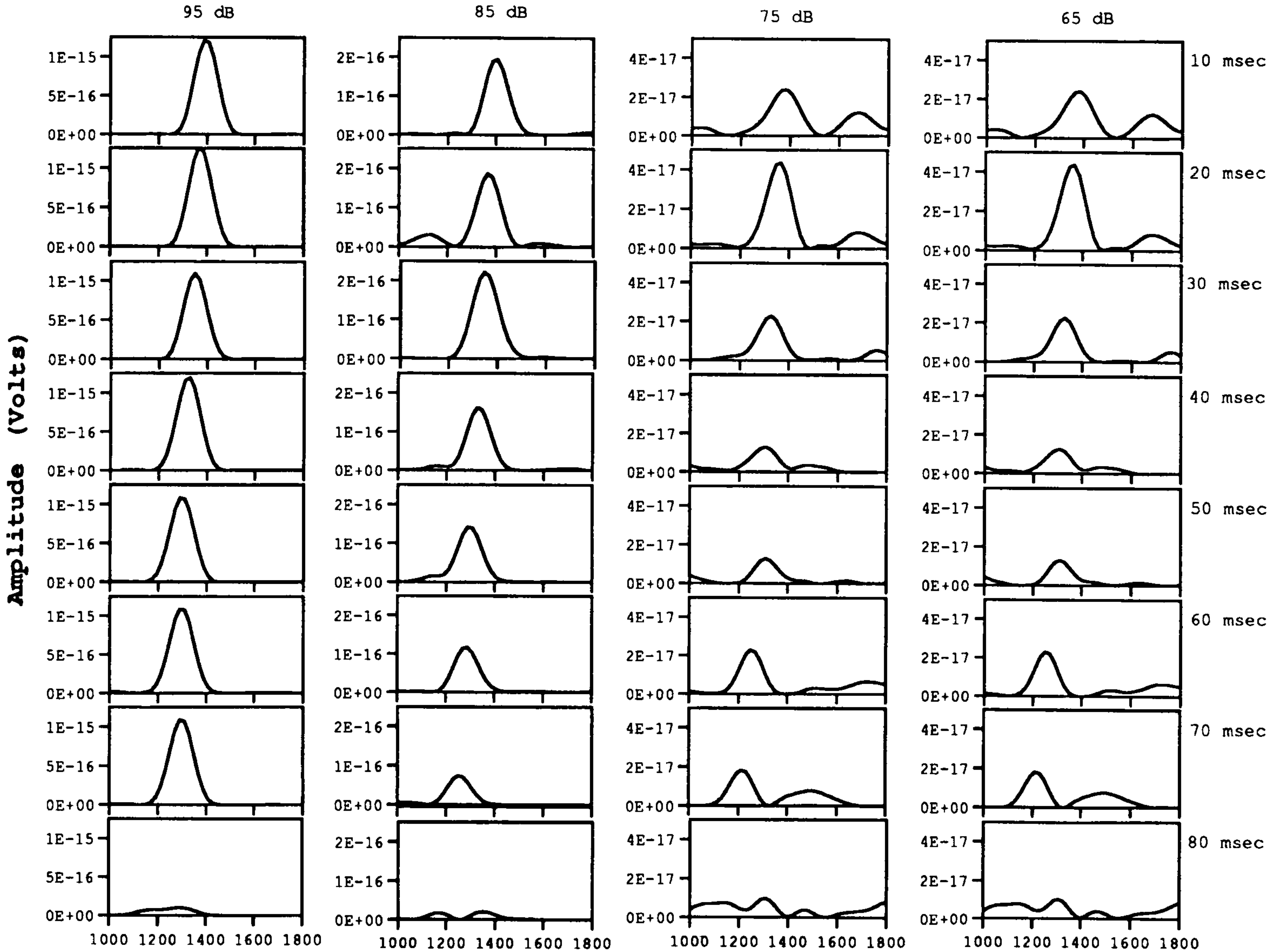


**Figure 13. Spectral data from summed FFR to the 1400 to 1200 Hz tonal sweep stimuli.**

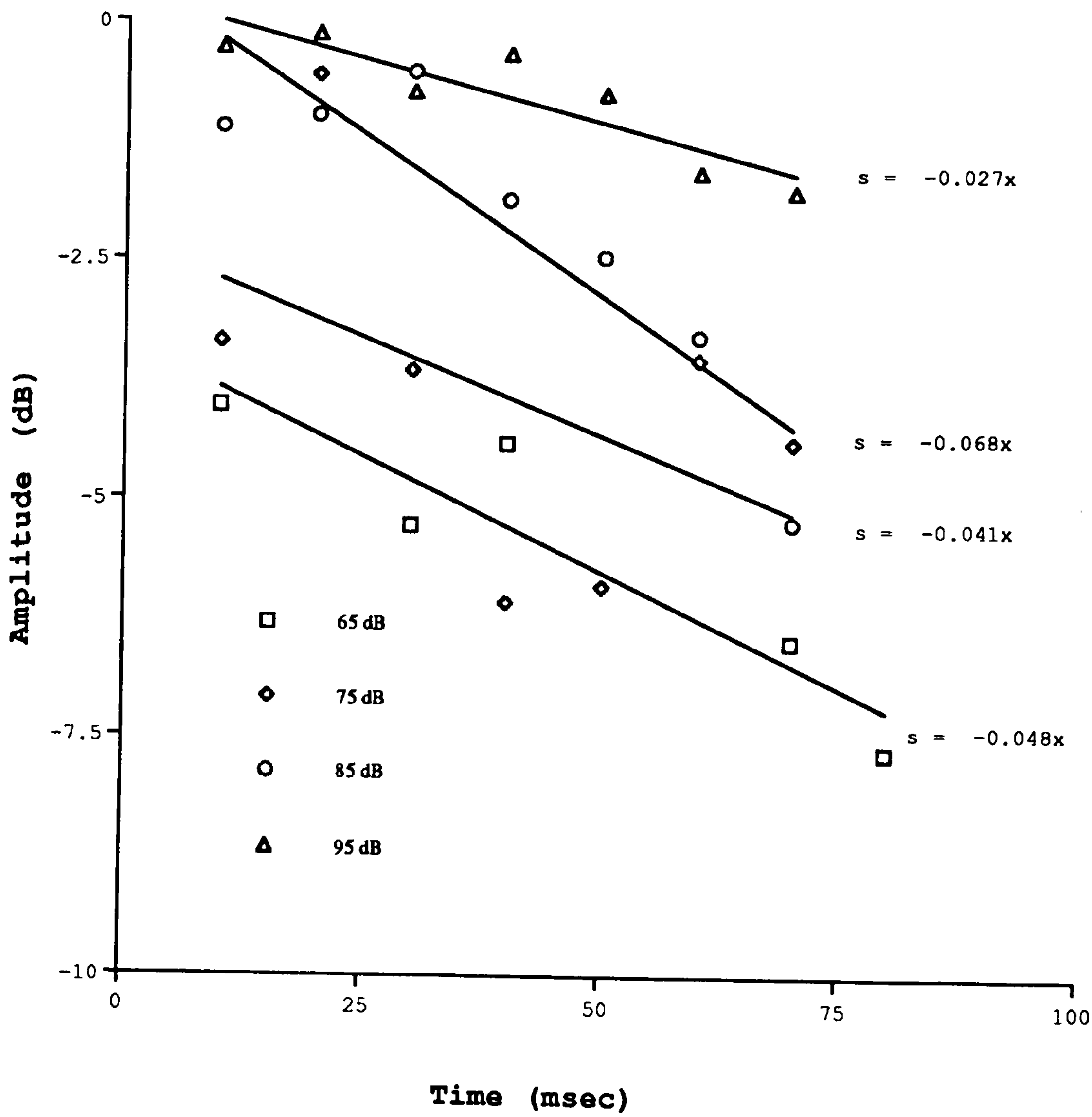


**Figure 14.** Mean amplitude of responses to the 1400 to 1200 Hz tonal sweep stimuli.

simple linear function of the form y=a+bx. The non-parallel lines indicates that the slopes of the amplitude change as a function of time are not the same across intensity levels. It appears that the slope of amplitude change as the intensity of the stimulus is increased remains essentially constant.

The rate of change of frequency is plotted as a function of time for the four stimulus levels in Figure 10. The results for the 1400-1200 Hz stimulus are represented by open diamonds. The data points were well fit by a simple linear function of the form y=a+bx. With the exception of the greater slope (3.341)observed for the 65 dB SPL condition, the essentially parallel functions for the other three levels (with an average slope value of 2.69) indicates that the rate of change of frequency is similar across these levels. Also, comparison of the data for the 1200-1400 Hz stimulus and the 1400-1200 Hz stimulus indicates that the rate of change of frequency in the FFR is faster for the 1400-1200 Hz stimulus than the 1200-1400 Hz stimulus. The quality of the fit and the slope values suggest that the frequency of the FFR is sweeping linearly at a rate of about 2.67 Hz/msec while the slope of the stimulus is about 2.5 Hz/msec. This slope value for the 1400-1200 Hz stimulus is similar to that observed for the two low frequency stimuli, and indicates the FFR well preserves the frequency change in the stimulus.

**Summary of Results**

1. FFR amplitude decreases and latency increases as stimulus intensity decreases with the exception of responses to the 600-400 Hz stimulus, for which amplitude gradually increases as a function of time.

2. Responses were more robust to lower frequency stimuli than to higher frequency stimuli.

3. FFR spectral peaks (both fundamental and harmonic) shift with the frequency sweep of the stimulus.

4. Spectral peak amplitude is more robust in responses to lower frequency stimuli.

5. FFR waveform amplitude decreases as a function decreasing stimulus intensity.

6. Amplitude also decreases as a function of time with the exception of responses to the 600-400 Hz stimulus, for which amplitude increases and the slope of the increase is steeper as a function of time.

7. The slope of the frequency change in the FFR well reflects the slope of the frequency of the respective stimuli.

# CHAPTER IV

## Discussion

The human FFR results from this study have confirmed the ability of the neural phase-locking mechanism to encode time-varying stimuli used in this study. In the following sections some of the response characteristics of the FFR to tonal sweeps that reflect this dynamic encoding mechanism in terms of intensity encoding and frequency encoding will be described.

### Intensity Encoding: Amplitude of the FFR

The FFR amplitude varied with intensity for all stimuli used in the study. This finding is not surprising given that the response amplitude of an evoked potential is directly proportional to the number of neural elements activated in a synchronous fashion. Thus with decrease in intensity the number of neural elements showing phase-locked activity will decrease and consequently the overall amplitude of the sustained response will decrease.

The FFR amplitude during upward sweep of both the 400-600 Hz stimulus and the 1200-1400 Hz showed amplitude reduction through the duration of the sweep (i.e as the frequency increased). These results are consistent with the results of other studies which show amplitude reduction of the FFR with increasing frequency over the range of 70 Hz to about 1800 Hz

(Glaser et al. 1976; Gardi, Merzenich, and McKean, 1979; Rickman and Chertoff, 1991; Pandya, 1996). Since the amplitude of the FFR is an index of the degree of phase-locking in the neural elements that generate the FFR, the amplitude reduction with time (therefore, frequency) is taken to mean that the ability of neurons to phase-lock decreases with increasing frequency. If this is the case then a downward sweep in the frequency should produce amplitude increment because ability to phase lock should improve with decreasing frequency. This is indeed what was observed for our 600-400 Hz stimulus. However, the amplitude decrease with time for the 1400-1200 Hz is inconsistent with this idea. It is not clear why the responses to the 1400-1200 Hz showed an amplitude reduction.

**Frequency Encoding: Rate of Change of frequency**

The ability of the human FFR to represent single frequency tones (Moushegian et al., 1973; Gerken et al., Glaser et al., 1976; Sohmer and Pratt, 1977; and Ananthanarayan and Durrant, 1992); multiple frequency steady-state tones (Galbraith and Brown, 1990; Galbraith, 1994; Greenberg et al., 1987; Pandya, 1996) and steady state synthetic vowels (Ananthanarayan, 1994) has been well demonstrated. The results of this study have clearly demonstrated that the human FFR reflecting sustained phase-locked neural activity in a population of neural elements in the rostral brainstem does indeed encode time-varying events in the stimulus. Specifically, the results showed that for all stimuli used and across all the four intensity levels there was a systematic shift in the frequency peak over time corresponding to the temporal change in frequency of the stimulus for both upward and downward sweeps of the stimuli. While there are no other published studies on FFR to time-varying stimuli, neurons at the auditory nerve level have shown the ability to encode (utilizing the mechanism of phase-locking) time-varying consonant-vowel syllables in a robust fashion (Young and Sachs, 1979; Miller and Sachs, 1983).

The observation that the rate of frequency change of the FFR (for all stimuli in general and for the upward sweeping stimuli in particular) over the sweep period approximates the rate of change of frequency for the corresponding stimulus indicates that this phase-locking ability is well synchronized with the stimulus frequency. The rate of change of frequency for the downward sweeping response tended to be slower than its stimulus counterpart. This means the rate of change of frequency for the upward sweeping response is faster than the rate of change of frequency observed for the downward sweeping response. To the extent that the difference between the responses to upward and downward sweep is true, it implies that the neurons are differentially sensitive to a rising frequency or a falling frequency.

The mechanism underlying the neural encoding of a steady-state stimulus is fairly straight forward in that the neural activity is phase locked to the individual cycles of the time invariant stimulus. However, with time-varying stimuli, such as the ones used in the present study, an additional dimension of time has to be represented in order for the phase-locked activity to encode time-varying events. It is quite possible that the encoding of the sweeping stimuli used in the study involves a progressive shift (upward or downward) in the neural population phase locked to the stimulus. This shift would occur along a tonotopically organized frequency map of the cochlea in the anatomical generator site of the FFR.

**Conclusion**

It has been established previously that a brainstem evoked response called the frequency-following response (FFR) is primarily responsible for the neural encoding of the pitch of time-invariant stimuli by a neural phenomenon referred to as phase-locking. The results of this study further characterize the FFR by showing it is also sufficiently dynamic for the neural encoding of time-varying stimuli, or stimuli whose frequency varies as a function of time. The stimuli used in this study were designed to approximate the time varying features of speech. Implications for this study include the possibility that the neural phase-locking reflected in the FFR may play a prominent role in the neural encoding of time-varying speech sounds, namely vowel sounds. It is possible that this neural encoding of time-varying features of speech sounds is degraded in individuals with hearing impairment. Consequently, FFRs in these individuals will reveal the nature of the degradation in neural encoding. Finally, it would be interesting to study whether FFRs to time-varying speech sounds may be used to evaluate neural maturation of the encoding process during the development of speech in children.

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# APPENDIX

# Informed Consent Form For Study

Title: Human Frequency-Following Response to Tonal Sweeps in Normal-Hearing Subjects.

## I. Description

You are being asked to participate in an experimental study aimed at evaluation how neurons in the lower part of the brainstem of normal hearing individuals respond in relation to stimuli whose frequency changes as a function of time, the results of which will be included in a master's thesis by Jeffery D. Parkinson. The responses recorded from the brainstem in this project are called frequency-following responses (FFRs). Should you agree to participate, the test session will not exceed two consecutive hours.

Before the study, you will be given a hearing test (tympanograms and routine audiometry) to make sure your hearing is within the range of normal (25 dB HL or better). Then FFRs will be recorded by placing electrodes, which are small metal discs, on your forehead and the back of your neck. The electrodes are held in place by electrode paste and plastic tape after the surface of the skin has been prepared with a mild abrasive solution. During the test session, you will be asked to simply remain still and relax in a reclining chair while you listen to a series of signals through headphones. Should you need to excuse yourself at any time, for any reason, during the test session, you will have a button to signal your request for attention.

The above test and procedures are routine clinical procedures which offer no known health risks. Regardless, every effort will be made to minimize any potential risk or discomfort. Although you may not benefit directly from this study, you will have contributed to our understanding of the way the brainstem encodes information that changes as a function of time.

## II. Confidentiality

Any information obtained about you for this study will be kept strictly confidential. Confidentiality of your data as will as any identifying material will be protected by limiting access to only the Principal and Co-Principal Investigators. Your identity will not be revealed in any description or publication of this research. This consent form will be stored for three years following completion of the study at a secured location at the University of

Tennessee.

III. Right To Refuse Or To End Participation

You are free to refuse to participate in this study or to withdraw at any time without having it affect your care in any of the University clinics and without any loss of benefits to which you might otherwise be entitled.

IV. Voluntary Consent

I have read the above information, and the Principal Investigator has explained the procedures and answered all my questions concerning this project. It has been explained to me that my identity will not be revealed in any description or publication of this research. Therefore, I consent to such publication for scientific purposes.

Any questions I have concerning my rights as a research subject will be answered by Jeffery D. Parkinson, the principal investigator, or Dr. A. K. Ananthanarayan, the Co-Principal investigator, at 570 South Stadium Hall. Telephone (423) 974-1811.

A copy of this consent form will be given to me.

My signature below means the I have had all my questions answered and freely agree to participate in the experimental study.

Signature of subject________________________ Date___________

V. Investigator's Certification

I certify that I have explained to the above individual the nature and purpose, the potential benefits, and the possible risks associated with participating in this experimental study. I have answered any questions that have been raised, and have witnessed the above signature.

Signature of investigator___________________ Date___________

VI. Extra Credit (Optional)

Prior to this session, my professor signed stating that credit would be given to me at the completion of my participation in the experimental study. My signature below means that I understand the terms under which I will receive credit.

Signature of subject________________________ Date__________

Signature of professor______________________ Date__________

# VITA

Jeffery David Parkinson was born in Farmington, Missouri on September 17, 1970. He graduated from Arkansas State University with a Bachelor of Science degree in General Studies in December 1994. He entered the graduate school at The University of Tennessee, Knoxville in August 1995 and earned a Master of Arts degree in Audiology on May 16, 1997. Future plans include completion of his clinical fellowship year in Audiology and the subsequent pursuit of a doctoral degree in Audiology with an emphasis in electrophysiology.