

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

**A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
313/761-4700 800/521-0600**

A

**FREQUENCY SPECIFICITY OF THE AUDITORY BRAINSTEM
AND THE MIDDLE LATENCY RESPONSES**

by

MARGARET ANN OATES

A dissertation submitted to the Graduate Faculty in Speech and Hearing
Sciences in partial fulfillment of the requirements for the degree of
Doctor of Philosophy, The City University of New York

1996

UMI Number: 9618088

**Copyright 1996 by
Oates, Margaret Ann**

All rights reserved.

**UMI Microform 9618088
Copyright 1996, by UMI Company. All rights reserved.**

**This microform edition is protected against unauthorized
copying under Title 17, United States Code.**

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

© 1996

MARGARET ANN OATES

All Rights Reserved

This manuscript has been read and accepted by the Graduate Faculty in Speech and Hearing Sciences in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

January 30, 1996
Date

David R. Stapells
David R. Stapells, Ph.D.
Chair of Examining Committee

January 30, 1996
Date

Irving Hochberg
Irving Hochberg, Ph.D.
Executive Officer

Supervisory Committee:

Arthur Boothroyd, Ph.D.
Graduate Center of CUNY

William Hal Martin, Ph.D.
Temple University

External Examiner:

Terence W. Picton, MD, Ph.D.
University of Toronto

THE CITY UNIVERSITY OF NEW YORK

ABSTRACT

FREQUENCY SPECIFICITY OF THE AUDITORY BRAINSTEM AND MIDDLE
LATENCY RESPONSES

by

MARGARET ANN OATES

Advisor: Professor David R. Stapells

This dissertation examined three controversial issues with respect to the frequency specificity of the Auditory Brainstem (ABR) and Middle Latency (MLR) Responses to brief tonal stimuli: (1) the use of low-frequency stimuli (i.e., 500 Hz) at high stimulus intensities for recording the ABR; (2) the suggestion that the MLR provides a more frequency-specific response to low-frequency tones compared to the ABR; and (3) the use of a nonlinear-gated stimuli (e.g., exact-Blackman-gated tone) versus conventional linear-gated stimuli to improve the frequency specificity of the ABR and/or MLR.

The frequency specificity of the ABR and MLR to 500- and 2000-Hz brief tones was investigated in 12 normal subjects using the high-pass noise/derived response technique ($\frac{1}{2}$ -octave- and 1-octave- wide derived bands). Stimuli were exact-Blackman- (5 cycles) and linear- (2-1-2 cycles) gated tones presented at 80 dB peak-to-peak equivalent (ppe) SPL. Cochlear contributions to ABR wave V-V' and MLR wave Na-Pa were assessed by: (1) effects of high-pass noise masking on response amplitudes and latencies; and (2) response amplitude profiles as a function of derived-band center frequency.

The high-pass noise and derived response results indicate that the ABR and MLR to 80 dB ppe SPL brief tones show good frequency specificity. The maxima in the ABR and MLR amplitude profiles occurred in the 500- and 707-Hz derived bands for the exact-Blackman- and linear-gated 500-Hz tones. The peak in the ABR amplitude profiles to both 2000-Hz stimuli was seen in the 2000-Hz derived band. For the MLR, the largest peaks in the amplitude profiles occurred in the 2000- and 1410-Hz derived bands for the exact-Blackman- and linear-gated tones. Cochlear contributions to the ABR and MLR to these tones were also present but smaller at 0.5 to 1 octave above and below the nominal frequencies of the stimuli. To summarize, ABRs and MLRs to 80 dB ppe SPL 500- and 2000-Hz brief tones show good frequency specificity and no significant differences were found in the frequency specificity of: (1) ABR versus MLR; (2) responses to 500- versus 2000-Hz tones; and (3) responses to exact-Blackman- versus linear-gated tones.

PREFACE

This thesis consists of three sections. Section I contains a review of the literature on the auditory brainstem (ABR) and middle latency (MLR) responses to tonal stimuli. The emphasis of this literature review is on the stimulus parameters that affect these responses. Section II contains a rationale for the thesis study, discussing the specific issues to be addressed, and providing a description of the stimulus, masker, and recording parameters employed in this study and their rationale. Section III consists of a manuscript to be submitted for publication, containing a description of the study and its results. The format of this manuscript is that required by the Journal of the Acoustical Society of America. This manuscript necessarily contains some information that has already been presented in sections I and II.

ACKNOWLEDGEMENTS

I would like to thank my advisor, David R. Stapells, for sharing his love of research with me. I am grateful for his support, encouragement, dedication, honesty and friendship throughout this thesis study. His "so?" and "why?" comments have helped me to broaden my knowledge and develop a questioning approach towards research.

I would like to express thanks to William (Billy) H. Martin and Arthur Boothroyd for their guidance while serving on my committee. In particular, Billy's enthusiastic messages of support and encouragement in weekly e-mail correspondence were appreciated as was his sense of humor and friendship.

I am also grateful to Terence W. Picton for serving as my external examiner and providing valuable feedback and suggestions on my dissertation.

Many thanks go to my "AEP lab" family (Brett, Vardit, Jo Manette, Cheng-Yuan, Sonja, Cynthia and Ruthie). I am especially appreciative of their support, friendship, and patience in dealing with my roller coaster of emotions and loquaciousness these last several years.

I would also like to acknowledge the financial assistance provided for this thesis study by the American Speech-Language-Hearing Foundation Student Research Grant (1993) as well as David R. Stapells' NIDCD grant 8P50 DC00223 (Cortical Event-Related Potentials in Hearing Loss).

Lastly, I would like to express my appreciation to my parents, Mike and Peggy, as well as my immediate family (Colleen, Carl, Tara, Kathy, Pierre, Michaela, Michael, Luz, Lauren, and Kevin). Their love, confidence, support and ability to make me laugh have made this achievement possible.

TABLE OF CONTENTS

COPYRIGHT PAGE	ii
APPROVAL PAGE	iii
ABSTRACT	iv
PREFACE	vi
ACKNOWLEDGEMENTS	vii
TABLE OF CONTENTS	ix
LIST OF TABLES	xiii
LIST OF FIGURES	xiv
SECTION I: FREQUENCY SPECIFICITY OF THE ABR AND THE MLR:	
REVIEW OF THE RELEVANT LITERATURE	1
A. Frequency Selectivity in the Peripheral Auditory System	2
B. Cochlear Physiology	3
C. VIIIth Nerve Physiology	5
D. Impact of Cochlear and VIIIth Nerve Physiology on the Frequency and Place Specificity of the ABR and MLR	7
E. Acoustics of Brief Stimuli	8
F. Description of the ABR and MLR	15
F1. Review of the Literature on ABRs to Tonal Stimuli	22
F1.A Effects of Stimulus Intensity	22
F1.B Effects of Stimulus Frequency	23
F1.C Effects of EEG Band Pass Filtering	24
F1.D Effects of Stimulus Rate	26
F1.E Effects of Stimulus Rise Time	27
F1.F Effects of Stimulus Temporal Shaping	32
F1.G Use of Masking	35
F1.G1 Masking to improve the frequency specificity of the ABR	35

F1.G2	Masking to investigate the frequency specificity of ABRs to different stimuli	37
F1.H	Effect of Stimulus Intensity on the Frequency Specificity of the ABR	40
F1.I	Problems with the 500-Hz ABRs	42
F1.I1	ABRs to clicks that have been masked with 500-Hz HP noise	43
F1.I2	500-Hz ABR derived responses using clicks	44
F1.I3	ABRs to 500-Hz tonal stimuli that have been masked with HP noise	44
F1.I4	Responses underlying the waveforms to 500-Hz tones: ABR versus MLR	45
F2.	Review of the Literature on MLRs to Tonal Stimuli	48
F2.A	Effects of Stimulus Intensity	48
F2.B	Effects of Stimulus Frequency	49
F2.C	Effects of EEG Band Pass Filtering	50
F2.D	Effects of Stimulus Rate	53
F2.E	Effects of Stimulus Rise Time	55
F2.F	Effects of Stimulus Temporal Shaping	56
F2.G	Effects of Masking on MLR to Tonal Stimuli	57
G.	The High-Pass Noise/Derived Response Technique	58
G1.	The Purposes of the HP/DR Technique	58
G2.	Description of HP/DR Technique	59
G3.	Validity of the HP/DR Technique	59
G4.	Advantages of the HP/DR technique Compared to Other Masking Techniques for Investigating the Frequency Specificity of Evoked Potentials	61
G5.	Disadvantages of the HP/DR Technique in Comparison to Pure-Tone and/or Notched Noise Masking in Determining the Frequency Specificity of the Response	61
G6.	Results from HP/DR Studies	62

SECTION II: RATIONALE UNDERLYING THE THESIS STUDY AND SELECTION OF SPECIFIC PARAMETERS	65
A. Rationale Underlying the Thesis Study	66
B. Description of Stimulus and Masking Parameters Employed in the Thesis Study	69
B1. Stimuli	69
B2. Stimulus Presentation Rate and Polarity	69
B3. Stimulus Intensity	70
B4. Earphone Transducers	73
B5. Intensity of Broadband Noise Masking	74
B6. HP Noise Cutoff Frequencies and Derived Bands	75
C. Description of Recording Parameters Employed in Thesis Study	76
C1. EEG Band Pass Filters and Rolloff Slope	76
C2. Electrode Montage	79
C3. Digitization Parameters	79
C4. Number of Response Replications and Trials	80
C5. Derived Responses	80
C6. Response Identification	80
C7. Response Criteria	83
 SECTION III: COCHLEAR CONTRIBUTIONS TO THE HUMAN AUDITORY BRAINSTEM AND MIDDLE LATENCY RESPONSES TO BRIEF TONES	 85
Abstract	87
Introduction	88
I. Methods	97
A. Subjects	97
B. Stimuli	97
C. Broadband and HP Noise Masking	98
D. Evoked Potential Recordings	100

	xii
E. Procedure	100
F. Derived Responses	101
G. Response Identification	103
H. Response Criteria	104
I. Response Measurements	104
J. Summary Statistics	105
K. Statistical Analyses	106
II. Results	107
A. Nonmasked Responses	107
B. HP Noise Masking	109
C. Full-Octave Derived Responses	119
D. Half-Octave Derived Responses	126
E. Full- and Half-Octave Derived Response Latencies . .	133
III. Discussion	138
A. Frequency Specificity of Evoked Potentials to Brief Tones	138
B. Frequency Specificity of the ABR <i>versus</i> the MLR . .	142
C. Frequency Specificity of Responses to 500- <i>versus</i> 2000-Hz Tones	143
D. Responses to Exact-Blackman- <i>versus</i> Linear-Gated Tones	144
E. ABRs and MLRs to 500- <i>versus</i> 2000-Hz Tones	147
F. Implications	150
Acknowledgements	153
LITERATURE CITED	154
VITA	179

LIST OF TABLES

SECTION II: RATIONALE UNDERLYING THE THESIS STUDY AND SELECTION OF SPECIFIC PARAMETERS

Table 1. Mean behavioral thresholds (dB ppe SPL) of subjects (N=10) to 500- and 2000-Hz exact-Blackman- and linear-gated tonal stimuli.	71
Table 2. Prediction of Maximum Temporary Threshold Shift (TTS) for 80 dB ppe SPL 500- and 2000-Hz tones. . . .	73
Table 3. Nominal and Calculated Derived-Band Center Frequencies (kHz)	77

SECTION III: COCHLEAR CONTRIBUTIONS TO THE HUMAN AUDITORY BRAINSTEM AND MIDDLE LATENCY RESPONSES TO BRIEF TONES

Table 1. Nominal and Calculated Derived-Band Center Frequencies (kHz)	102
Table 2. Mean absolute latencies and peak-to-peak amplitudes for ABR V and MLR Pa to 80 dB ppe SPL 500- and 2000-Hz nonmasked tones	109
Table 3. Results of 3-way Repeated Measures Analyses of Variance for Amplitude Profiles for the HP Noise Conditions	115
Table 4. Results of 3-way Repeated Measures Analyses of Variance for the Absolute Latencies of Waves V and Pa for the HP Noise Conditions	118
Table 5. Results of 3-way Repeated Measures Analyses of Variance for Full-Octave Derived Responses	123
Table 6. Mean Summary Statistics for One-Octave-Wide Derived Responses to 500- and 2000-Hz exact-Blackman- and Linear-Gated Tones	127
Table 7. Results of 3-way Repeated Measures Analyses of Variance for Half-Octave Derived Responses	132
Table 8. Mean Summary Statistics for Half-Octave-Wide Derived Responses to 500- and 2000-Hz exact-Blackman- and Linear-Gated Tones	134
Table 9. Mean ABR wave V and MLR wave Pa latencies for full-octave and half-octave derived responses to 80 dB ppe SPL 500- and 2000-Hz exact-Blackman- versus linear-gated tones	137

LIST OF FIGURES

SECTION I: FREQUENCY SPECIFICITY OF THE ABR AND THE MLR: REVIEW OF THE RELEVANT LITERATURE

Figure 1.	Two methods to measure the sound pressure level for transient stimuli: peak SPL and peak-to-peak (ppe) SPL	10
Figure 2.	Acoustic spectra for exact-Blackman- versus linear-gated 500- and 2000-Hz tones	14
Figure 3.	Time waveforms for the 500- and 2000-Hz exact-Blackman- and linear-gated tones	15
Figure 4.	Grand mean nonmasked ABRs and MLRs to 80 dB ppe SPL 500- and 2000-Hz tones	18
Figure 5.	Derived response amplitude profiles for ABR wave V to click and tonal stimuli (adapted from Kramer, 1992)	63

SECTION II: RATIONALE UNDERLYING THE THESIS STUDY AND SELECTION OF SPECIFIC PARAMETERS

Figure 1.	Electrical spectra of pink noise, the 9 HP noise conditions, and the derived bands obtained by subtraction of HP noise maskers separated by full and half octaves	78
-----------	---	----

SECTION III: COCHLEAR CONTRIBUTIONS TO THE HUMAN AUDITORY BRAINSTEM AND MIDDLE LATENCY RESPONSES TO BRIEF TONES

Figure 1.	Acoustic spectra for exact-Blackman- versus linear-gated 500- and 2000-Hz tones	98
Figure 2.	Electrical spectra for pink noise, the 9 HP noise conditions, and the derived bands obtained by subtraction of HP noise maskers separated by full and half octaves	99
Figure 3.	Grand mean nonmasked waveforms recorded to 80 dB ppe SPL 500- and 2000-Hz exact-Blackman- versus linear-gated tones	108
Figure 4.	Grand mean waveforms recorded to 80 dB ppe SPL 500- and 2000-Hz tones recorded in 9 HP noise conditions	111
Figure 5.	Mean response amplitude profiles for ABR wave V-V' and MLR wave Na-Pa to the 500- and 2000-Hz tones recorded in HP noise masking conditions	113

Figure 6.	Mean waves V and Pa latencies to the 500- and 2000-Hz stimuli as a function of HP noise cutoff frequency	116
Figure 7.	Grand mean full-octave derived response waveforms to 80 dB ppe SPL 500- and 2000-Hz tones	121
Figure 8.	Mean one-octave-wide derived band response amplitude profiles for ABR wave V-V' and MLR wave Na-Pa	122
Figure 9.	Grand mean half-octave derived response waveforms to 80 dB ppe SPL 500- and 2000-Hz tones	129
Figure 10.	Mean half-octave-wide derived band response amplitude profiles for ABR wave V-V' and MLR wave Na-Pa	130

SECTION I

**FREQUENCY SPECIFICITY OF THE ABR AND THE MLR:
REVIEW OF THE RELEVANT LITERATURE**

A. Frequency Selectivity in the Peripheral Auditory System

The mechanical response of the basilar membrane and its interaction with the cochlear hair cells and auditory neurons form the foundation for the frequency selectivity at higher levels of the auditory system (Cody and Russell, 1987; Johnstone, Patuzzi, and Yates, 1986; Khanna and Leonard, 1982; Pickles, 1988; Robles, Ruggero, and Rich, 1986; Ruggero, 1992; Ruggero and Rich, 1991; Sellick, Patuzzi, and Johnstone, 1982). Frequency selectivity is the ability of the auditory system to resolve the frequencies present in a complex signal. The analysis of the frequency content of an auditory stimulus takes place at all levels of the auditory system and has been investigated by the use of frequency threshold or tuning curves (FTCs). FTCs are measured by determining the stimulus intensity needed to reach a certain criterion threshold over a wide range of frequencies. These curves usually consist of a tip which occurs at the frequency to which the neuron or hair cell is best tuned. This frequency is known as the characteristic frequency (CF) of the auditory neuron(s) or hair cell. The tuning curves also have response areas that extend to frequencies above and below the CF. This response area denotes the areas of frequency and intensity that will cause the neuron(s) to respond when above its criterion threshold. The degree of frequency selectivity of the FTCs has been expressed in two ways: (1) the slopes of the tuning curves above and below the CF and (2) the bandwidth of the tuning curve at a fixed intensity above the threshold at the CF (Pickles, 1988). Generally a quality factor, known as a "Q10" factor, is used to estimate bandwidth and this is defined as the characteristic frequency divided by the bandwidth at 10 dB above the

best threshold. FTCs permit the direct comparison of the frequency-selective properties that exist at various levels of the auditory system.

The following is a brief discussion of how cochlear and VIIIth-nerve physiology determines the frequency-selective properties of the peripheral auditory system and the impact this physiology has on the frequency and place specificity of the auditory brainstem and middle latency responses.

B. Cochlear Physiology

The frequency selectivity of the cochlea depends upon the mechanics of the basilar membrane and the cochlear fluids, and their interactions with the hair cells. Vibrations of the stapes in the round window initiate a travelling wave of displacement on the basilar membrane, first discovered by von Békésy in 1960. The travelling wave moves from the base to the apex of the cochlea. For a stimulus of a fixed frequency, the vibration of the cochlear partition grows in amplitude as the wave moves away from the stapes, reaches a maximum amplitude, and dies out rapidly beyond this maximum. The location of this maximum peak depends on the frequency of the stimulus. High-frequency steady-state sounds vibrate only the basal regions of the cochlear partition, while low-frequency sounds vibrate all the regions of the cochlear partition with the greatest amplitude occurring in the apical region. Therefore, the travelling wave results in "place coding" for frequency along the basilar membrane. The travelling wave moves more slowly as it travels up the cochlea. It takes approximately 5 ms to travel from the base to the apex. As a result, responses to low-frequency sounds at the apical end of the cochlea are initiated later than responses to high-frequency sounds, and the amount of the basilar

membrane that is activated by a particular frequency increases as the wave travels from the base to the apex. Thus, the traveling wave acts as a series of sequential asymmetrical low-pass filters (Békésy, 1960).

FTCs have shown that the mechanical response of the basilar membrane acts as a band-pass filter and has a high degree of frequency selectivity at low stimulus intensities (Johnstone *et al.*, 1986; Khanna and Leonard, 1982; Robles *et al.*, 1986; Ruggero, 1992; Ruggero and Rich, 1991; Sellick *et al.*, 1982). Basilar membrane tuning curves have low-intensity sharply-tuned tips at the CF with a steeply-sloping high-frequency edge and a less steeply sloping low-frequency tail. At moderate to high stimulus intensities (60-80 dB SPL), the basilar membrane response becomes more broadly tuned and the tip of the tuning curves shifts toward the lower frequencies (Johnstone *et al.*, 1986; Robles *et al.*, 1986; Ruggero, 1992; Ruggero and Rich, 1991; Sellick *et al.*, 1982). This occurs because there is saturation of the basilar membrane vibrations at or near its CF as stimulus intensity is increased, while the response continues to grow linearly at lower frequencies. The FTCs of the basilar membrane and the VIIIth-nerve fibers have very similar characteristics, especially in the region of the tip and in the slope of their high-frequency edges (Khanna and Leonard, 1982; Robles *et al.*, 1986; Sellick *et al.*, 1982). The mechanical response of the basilar membrane depends on a normal functioning organ of Corti, and recent evidence suggests that the outer hair cells account for a large part of the sensitivity and frequency-selective properties of the basilar membrane (e.g., Ruggero, 1992; Ruggero and Rich, 1991).

Russell and Sellick were the first investigators to make intracellular recordings from mammalian inner hair cells (Russell and Sellick, 1978). These hair cells also have FTCs characterized by low-

threshold, sharply-tuned tips at their CF, and a high-threshold less steeply sloping low-frequency tail. The shape of the tuning curves for the inner hair cells corresponds to those of the mechanical response of the basilar membrane. There are, however, possibly some differences in the low-frequency tails (Pickles, 1988). The effect of stimulus intensity on the inner hair cells are similar to that seen with the basilar membrane response (Dallos, 1985; Russell and Sellick, 1978). Specifically, there is a linear growth in the receptor potential at the low stimulus intensities. When stimulus level is increased, however, the response saturates for frequencies at or near the CF. The FTCs measured from outer hair cells are very similar in terms of their characteristic frequencies, high-frequency slope, low-frequency slope, and tip-to-tail ratios when compared to inner hair cells (Cody and Russell, 1987). Cody and Russell also reported that the intensity functions for outer hair cells are comparable to those of inner hair cells, however the response of the outer hair cells saturates more abruptly at high stimulus intensities.

C. VIIIth Nerve Physiology

Studies of VIIIth-nerve fibers show that each neuron, relative to its placement along the basilar membrane, is best tuned to a frequency, known as its CF. At the CF, the auditory neuron requires the least stimulus energy to reach a criterion threshold. This criterion threshold rises rapidly for frequencies both above and below this CF. The shape of the FTCs for individual auditory neurons vary with stimulus frequency. For low frequencies (i.e., less than 1000 Hz), the tips of the tuning curves are more rounded and the low- and high-frequency slopes are symmetric. At higher frequencies, the tuning curves become increasingly asymmetric and have very sharply-tuned tips with steep high-frequency

slopes, and less-steep low-frequency slopes. The high-frequency slopes of auditory nerve fibers with CFs of 8000-10,000 Hz, measured at 5-25 dB above the tip of the tuning curve, ranged from 100-600 dB/octave, while the range for the low-frequency slopes was from 80-250 dB/octave (Dallos, 1985; Evans, 1975; Robles et al., 1986; Ruggero and Rich, 1991). These values are in close agreement with the high- and low-frequency slopes reported by Cody and Russell (1987) for the inner and outer hair cells in the high-frequency region. The Q10 values for these auditory neurons with high CFs also coincide with those reported for the basilar membrane and hair cells (Cody and Russell, 1987; Robles et al., 1986; Russell and Sellick, 1978; Sellick et al., 1982).

The coding of frequency information in the auditory neuron is also accomplished by phase locking. Kiang (1965), and Rose, Brugge, Anderson, and Hind (1967), demonstrated that single auditory neurons with CFs of less than 4000-5000 Hz tend to discharge once per cycle to low-frequency tones (i.e., ≤ 1000 Hz). This discharge pattern is in cadence with the period of the stimulus. At higher stimulus frequencies, auditory neurons cannot discharge to every cycle of the stimulus due their absolute refractory periods (Kiang, 1965; Rose et al., 1967). Instead, these auditory neurons with high CFs discharge to every other or every third cycle of the stimulus. Phase locking occurs regardless of stimulus intensity, and is maintained even if the stimulus frequency is not the CF of the auditory neuron (Kiang, 1965; Rose et al., 1967).

Several researchers have investigated the effects of stimulus intensity on the discharge rates of auditory neurons as a function of stimulus frequency (e.g., Anderson, Rose, Hind, and Brugge, 1970; Kiang, Sachs, and Peake, 1967; Rose, Hind, Anderson, and Brugge, 1971). These studies have demonstrated that as stimulus intensity is increased, there is an increase in the excitation area along the cochlear partition. For

nerve fibers with low CFs, the response area becomes asymmetric with increases in intensity and is skewed toward the higher frequencies. In contrast, the response area for fibers with high CFs (i.e., > 2000 Hz) spreads toward the lower frequencies with increases in stimulus intensity.

D. Impact of Cochlear and VIIIth Nerve Physiology on the Frequency and Place Specificity of the ABR and MLR

The spread of excitation along the cochlear partition that occurs with higher stimulus intensities has a direct impact on the frequency and place specificity of the auditory brainstem and middle latency responses. Frequency specificity of an audiometric measure is a term generally applied to the evaluation of thresholds, and refers to how independent a threshold at one stimulus frequency is of contributions from surrounding frequencies (Stapells, Picton, and Durieux-Smith, 1994; Stapells, Picton, Pérez-Abalo, Read, and Smith, 1985). Place specificity, on the other hand, refers to the portion of the cochlear partition contributing to the response. These two properties of the response may or may not be in agreement. When frequency specificity is poor, the auditory thresholds measured at one frequency may not be accurate due to the influences coming from cochlear places most sensitive to the given stimulus (Stapells et al., 1994, 1985). At moderate to high stimulus intensities, which are often the levels at which ABR and MLR testing are conducted, the high-frequency regions of the cochlea will respond to low-frequency stimuli even though the place for maximum response for these signals may be closer to the apex. This occurs because of stimulation of the low-frequency tails of fibers with high characteristic frequencies (e.g., Kiang and Moxon, 1974; Kiang et al., 1967; Özdamar and Dallos, 1976).

A way to improve the frequency and place specificity of these electrophysiologic responses is to use some form of noise masking, to be discussed in further detail in the masking section of this review. Masking produced by pure tones or by narrow-band noise is symmetrical around the masker frequencies for low masker levels (20-40 dB SPL), but becomes asymmetrically wider with increasing masker intensity (Egan and Hake, 1950; Ehmer, 1959a,b). At masker intensities of 80 dB SPL, the greatest masking occurs for tones higher than the masker frequency with very little masking occurring at frequencies below the tonal stimulus. This asymmetric masking pattern is referred to as upward spread of masking (Ehmer, 1959a). The masking patterns are very wide for low-frequency maskers and become more restricted for high-frequency maskers.

A clinical application of electrophysiologic testing is the assessment of peripheral hearing sensitivity in children and/or adults who cannot be tested reliably with conventional behavioral audiometric techniques. Both the ABR and MLR have been suggested for use in estimating pure-tone behavioral thresholds, thus highlighting the importance of defining the frequency and place specificity of these responses. Researchers have been searching for ways that the stimuli and/or masking techniques can be presented to yield the most frequency-specific ABRs and/or MLRs that best predict the pure-tone behavioral audiogram. The following is a discussion of the types of stimuli that are used in recording these responses.

E. Acoustics of Brief Stimuli

The brief stimuli that are required for recording the auditory evoked potentials are quite different from the long-duration pure tones used in conventional behavioral audiometry. The spectral content of these brief stimuli refers to the amount of energy present in the

acoustical or input signal (i.e., the stimulus) as a function of frequency. The acoustical spectrum is determined by the rise/fall time, duration, frequency and intensity of the stimulus as well as by the transfer characteristics of the transducer. Fast Fourier transforms (FFTs) analyze the complex stimulus waveform into its individual frequency components.

The intensity of these brief stimuli is described in terms of sound pressure level (SPL). Sound pressure is expressed in decibels sound pressure level, where $\text{dB SPL} = 20 \log(P_o/P_{\text{ref}})$. P_o = pressure in $\mu\text{pascals}$ and $P_{\text{ref}} = 20 \mu\text{pascals}$. Presently, the two most commonly used methods to measure the sound pressure level of a transient stimulus are: (1) peak SPL and (2) peak-to-peak equivalent (ppe) SPL. Peak SPL is the intensity or amplitude of the sound at the peak of the pressure change (Stapells, Picton, and Smith, 1982). It is measured by using a sound level meter with a "peak-hold" capability, such as the Brüel and Kjaer model 2209, which indicates the maximum peak pressure (for transients as brief as $50 \mu\text{s}$) and holds the meter to this maximum pressure until it is reset. Peak SPL is measured from the baseline of the stimulus to its peak (see Figure 1). In contrast, peak-to-peak equivalent (ppe) SPL is equal to the numerical value of the root-mean-square (rms) sound pressure or amplitude of a long-duration sinusoidal signal which, when fed to the same transducer under the same test conditions, has the same peak-to-peak sound pressure or amplitude as the short-duration signal (International Electrotechnical Commission, 1994). For ppe SPL measures, the AC output of the sound level meter is routed to an oscilloscope. The ppe SPL is measured by recording the peak-to-peak amplitude of the transient stimulus, adjusting the steady-state tone to an equivalent amplitude and then measuring the amplitude of the continuous tone from the output of the sound level meter on an oscilloscope (see Figure 1).

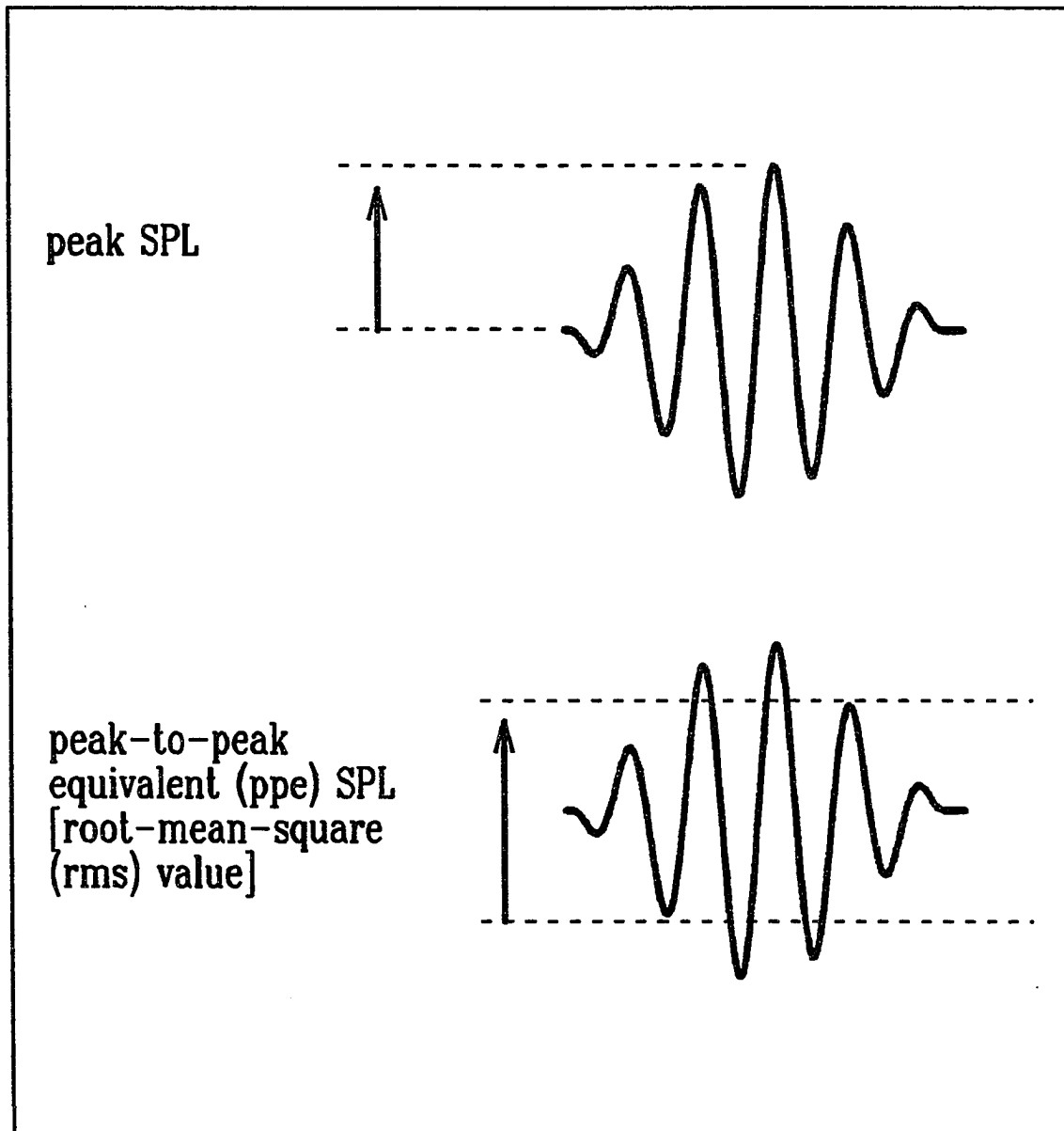


Figure 1. Two methods to measure the sound pressure level (SPL) for transient stimuli: peak SPL (top) and peak-to-peak equivalent (ppe) SPL (bottom).

The two types of stimuli that are typically used in conducting ABR and MLR evaluations are clicks and brief tones. Clicks produced by passing a 100- μ s square wave through a TDH-49 earphone result in an acoustic waveform containing equal energy from approximately 100 to just below 8000 Hz (Stapells et al., 1982). In contrast, brief tones have a concentration of energy at the nominal frequency of the tone and sidebands of energy at lower and higher frequencies (Burkard, 1984; Durrant, 1983; Gorga and Thornton, 1989; Harris, 1978; Laukli, 1983, Nuttall, 1981; Pfeiffer, 1974).

Because both clicks and brief tones contain energy over a range of frequencies, electrophysiologic responses to these stimuli may be evoked by any of the frequencies present in the spectrum. The spread of energy to frequencies other than the nominal frequency is known as "spectral splatter" (Durrant, 1983). The degree of spectral splatter is influenced by the rise time, duration, intensity, and temporal shaping (e.g., linear versus nonlinear) of the stimulus, as well as by the type of transducer employed (Burkard, 1984; Durrant, 1983; Laukli, 1983; Pfeiffer, 1974; Stapells and Picton, 1981).

A reasonably efficient method for obtaining a frequency-specific evoked potential is to use stimuli with energy concentrated in a restricted frequency range around the frequency of interest (i.e., brief tones) rather than a broadband stimulus (i.e., a click). When employing brief tonal signals, however, there is a trade-off between the brief duration of the tone and its frequency specificity (Davis, 1976; Gabor, 1947). The rise time of the signal must be brief in order to initiate a synchronized neural discharge from the individual auditory neurons. Short rise times, however, lead to an increase in the spread of spectral energy, thus decreasing frequency specificity. There are two ways of specifying rise times for brief tones used in recording

electrophysiologic responses: (1) tones with rise times consisting of a constant number of cycles, and (2) tones with rise times of a constant duration in ms, regardless of the stimulus frequency. For rise times consisting of a constant number of cycles, the duration of the tone will vary with stimulus frequency. The advantage of having the rise/fall times and plateaus of the tone constant in terms of number of cycles is that the acoustic power spectra of the tone for all stimulus frequencies have the same shape and width on a logarithmic frequency scale. In contrast, for tones with fixed rise times (i.e., constant duration) the temporal features of the stimulus are constant, but the spectral splatter will be greater for the lower versus higher frequencies.

The most widely used tonal stimuli in clinical settings are linear-gated brief tones. There are, however, a number of nonlinear-gating functions (e.g., cosine, exponential, Gaussian, Hanning, Kaiser-Bessel, exact-Blackman) which theoretically can yield frequency spectra that are more narrow than those of linear-gated tones, while still maintaining the rapid stimulus onset needed for eliciting the ABR (Gorga and Thornton, 1989; Harris, 1978; Nuttal, 1981). The differences between the spectra of the linear- and nonlinear-gated stimuli are in the width of the main energy lobe, the amplitudes of the sidelobes of energy, and the rate of decay of the sidelobes. These differences are independent of stimulus frequency.

Several investigators have claimed that the frequency specificity of the ABR may be improved by the use of a Blackman-gated tone in place of the linear-gated stimulus (e.g., Gorga, Beauchaine, Kaminski, and Bergman, 1992; Gorga and Thornton, 1989; Telian and Kileny, 1989). As displayed in Figure 2, if a 2000-Hz tonal stimulus with a five-cycle total duration is employed, the acoustic spectrum of the exact-Blackman-gated tone has energy in the sidelobes 68 dB below the peak energy of

the main lobe, an approximate 1773 Hz main-energy lobe (at 20 dB below the peak energy) and a 6 dB/octave rolloff thereafter (Nuttall, 1981). In contrast, the linear-gated "2-1-2" cycle tone, --recommended for frequency-specific testing by Davis (1976) and by Davis, Hirsh, Popelka, and Formby (1984)-- has sidelobes of energy approximately 27 dB below the amplitude of the main energy lobe, an approximate width of 1239 Hz for the main energy lobe (20 dB below the peak) and an 18 dB/octave slope thereafter. No plateau portion was employed with the exact-Blackman-gated tones in this study as the use of a plateau narrows the width of the main energy lobe and adds higher sidelobes of energy (Gorga and Thornton, 1989), thus reducing the spectral differences between these two temporal envelopes. The acoustical frequency spectrum differences between the "2-1-2" cycle linear- versus exact-Blackman-gated 500- and 2000-Hz tonal stimuli employed in this thesis study are displayed in Figure 2. The reduction of energy in the sidelobes of the exact-Blackman-gated tone compared to the linear may have the advantage of removing contributions to the ABR and/or MLR from frequencies other than the nominal frequency, and thus yield more frequency-specific responses than would have been obtained with a linear-gated signal (Gorga and Thornton, 1989). This may not be the case, however, because evoked potentials to the exact-Blackman-gated tones may show poorer frequency specificity compared to responses to the linear-gated tones because there may be contributions to the response from frequencies represented by the wider main lobe of the exact-Blackman-gated tone.

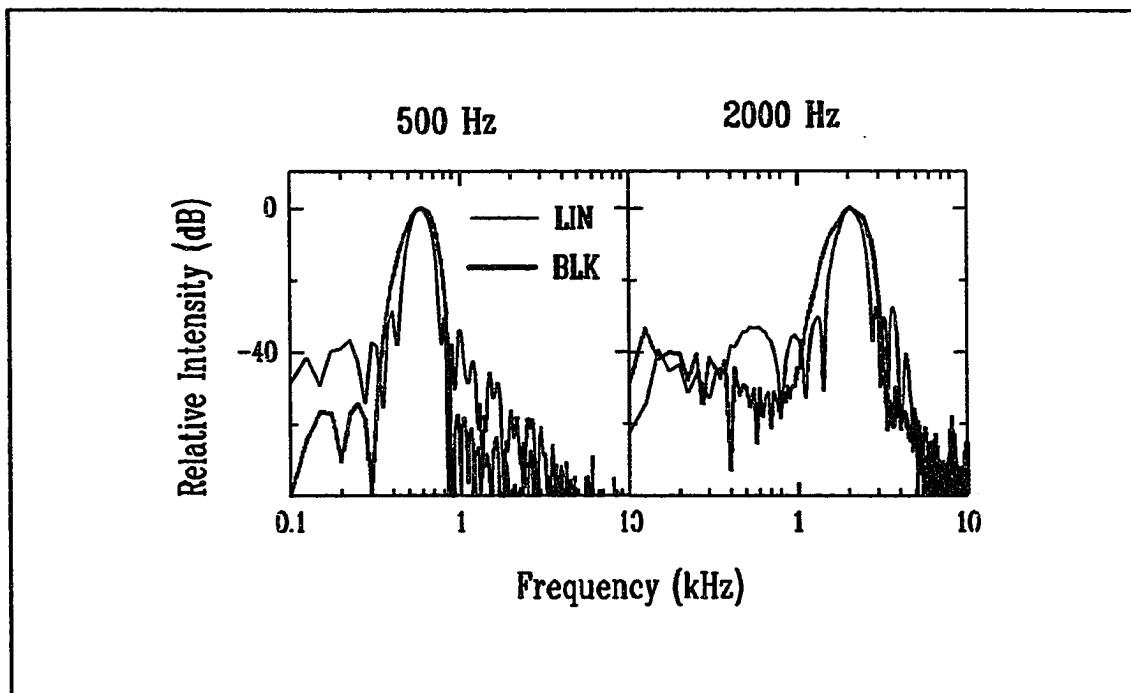


Figure 2. Acoustic spectra for exact-Blackman- versus linear-gated tones for 500 Hz (left) and 2000 Hz (right).

The amplitude at point n in the exact-Blackman-gated stimuli employed in this study is given by the formula:

$$W(n) = 0.42 + 0.50 \cos[2\pi/N \times n] + 0.08 \cos [2\pi/N \times 2n],$$

where N is the total number of points in the window and n goes from $-N/2$ to $+N/2$ (Harris, 1978; Nuttall, 1981). In contrast, the formula used for computing the linear-gated tones was:

$$W(n) = 1.0 - [n - 0.5(N-1)] \div 0.5(N+1).$$

The time waveforms for the exact-Blackman- versus linear-gated tonal stimuli for the 500- and 2000-Hz tones are displayed in Figure 3.

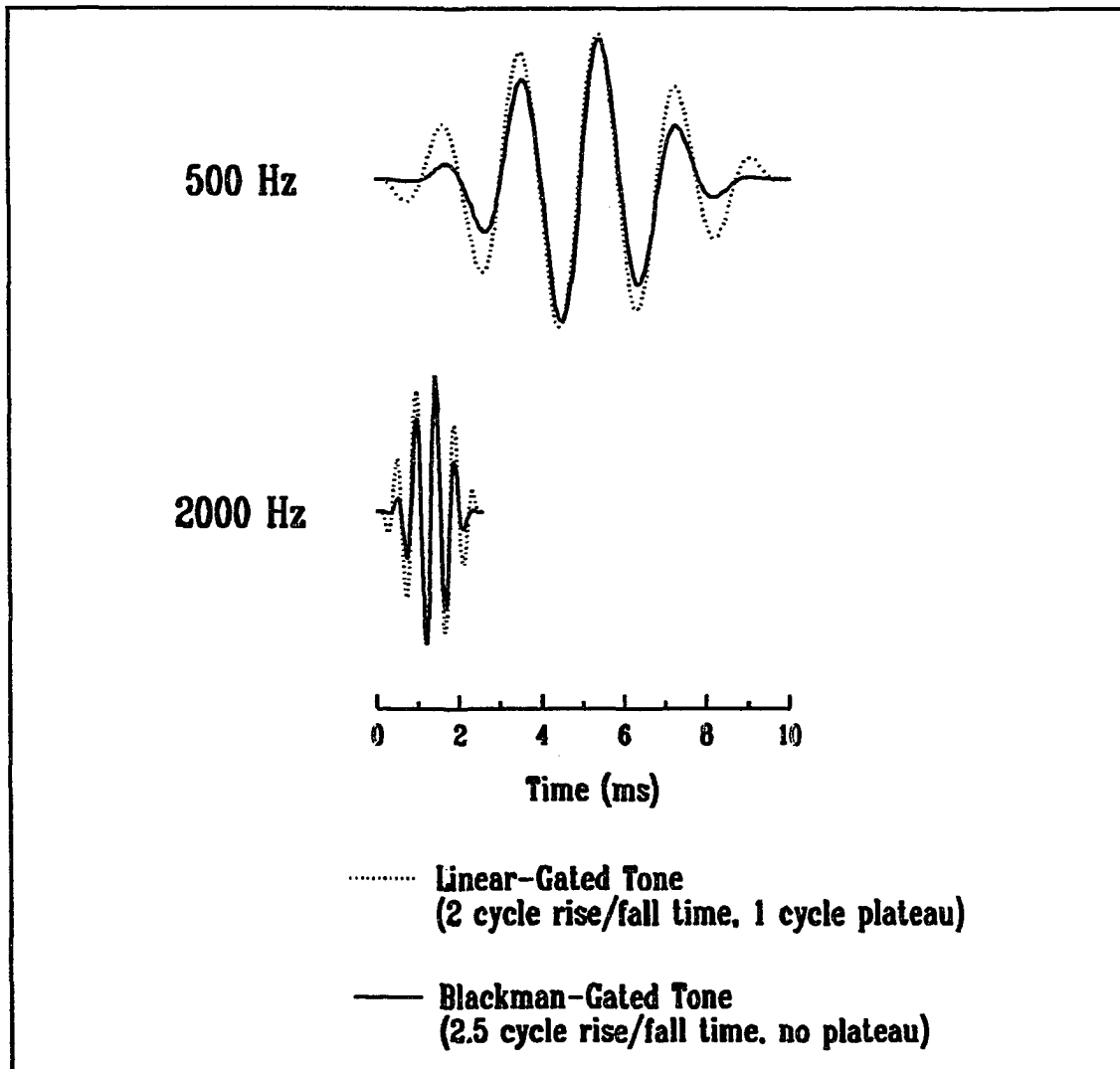


Figure 3. Time waveforms for the 500 Hz (top) and 2000 Hz (bottom) exact-Blackman- versus linear-gated tones.

F. Description of the ABR and MLR

The auditory brainstem (ABR) and middle latency (MLR) responses are "far-field" auditory evoked potentials that are recorded to transient stimuli usually from electrodes placed on the vertex and either the ipsilateral and/or contralateral mastoids. The ABR to high-intensity clicks is characterized by a series of vertex-positive and

negative waves that are recorded in approximately the first 10-12 ms following stimulus onset. The major vertex-positive peaks in the response have been assigned Roman numerals from I to VII, according to a classification system developed by Jewett and Williston (1971). In contrast, the ABR to tonal stimuli and to low-intensity clicks consists primarily of wave V-V'. In the Auditory Evoked Potentials (AEP) Laboratory at the Albert Einstein College of Medicine, ABR wave V to tonal stimuli in normal-hearing adults has been defined as the maximum vertex-positive peak occurring between 6 and 20 ms following stimulus onset (Wu and Stapells, 1994; Wu and Stapells, in preparation). If several peaks of equal amplitude occur within this range, the peak preceding the largest negativity is labeled as wave V. Wave V' has been defined as the most prominent negativity occurring within 8 ms of the latency of wave V (Stapells and Picton, 1981; Noursak and Stapells, 1992).

It has been demonstrated that the ABR consists of at least two main components, known as the "fast" and "slow" components (Davis and Hirsh, 1979; Suzuki, Hirai, and Horiuchi, 1977; Takagi, Suzuki, and Kobayashi, 1985). The fast component consists of a series of successive positive and negative waves and is dominated by the high-frequency components of the ABR. The slow component, in contrast, is characterized by a broad positive wave which is followed by a prominent vertex-negative wave, known as V' (Stapells and Picton, 1981) or as the "slow-negative wave at 10 ms (SN10)" (Davis and Hirsh, 1979). The slow positive-negative wave of the ABR reflects low-frequency electroencephalographic (EEG) activity (Takagi et al., 1985). The fast and slow components of the ABR vary with rise time, stimulus intensity, and stimulus frequency, and will be discussed in further detail in this review of the literature.

The middle latency response consists of a sequence of negative-positive waves, with three main peaks labeled as Na, Pa, and Nb (e.g., Kileny, 1983; Özdamar and Kraus, 1983; Picton, Hillyard, Krausz, and Galambos, 1974). Wave Pa is the most reliable and robust of these responses (Kileny, 1983). The following latency ranges for the MLR waves to tonal stimuli in normal-hearing adults have been employed in the AEP laboratory at the Albert Einstein College of Medicine: wave Na is defined as the largest negativity following wave V and occurring between 10 and 30 ms. Wave Pa is the largest positivity following Na and occurring between 20 and 50 ms and wave Nb is the largest negativity following Pa and occurring between 30 and 75 ms (Mackersie, Down, and Stapells, 1993; Wu and Stapells, 1994; Wu and Stapells, in preparation). [Another wave, sometimes referred to as Pb, is more likely wave P1 of the obligatory cortical auditory evoked potential (Erwin and Buchwald, 1986). It is not included in this review of the MLR.] Figure 4 shows the grand mean (N=12) subjects nonmasked ABRs and MLRs recorded to 80 dB ppe SPL 500- and 2000-Hz linear (2-1-2 cycle) tones. The ABR and MLR to the 500-Hz tones have longer latencies in comparison to the responses to the 2000-Hz tones. These latency differences reflect the longer travel time to the apical regions of the cochlea as well as differences in the rise time of the stimuli (discussed in further detail in the results section). The waveform morphology of the ABR to the low-frequency tonal stimulus is broader compared to the response to the higher-frequency tone. The peak-to-peak amplitudes of ABR wave V-V' are approximately equal at both stimulus frequencies, whereas the amplitude of MLR wave Na-Pa is larger to the lower versus higher frequency tones.

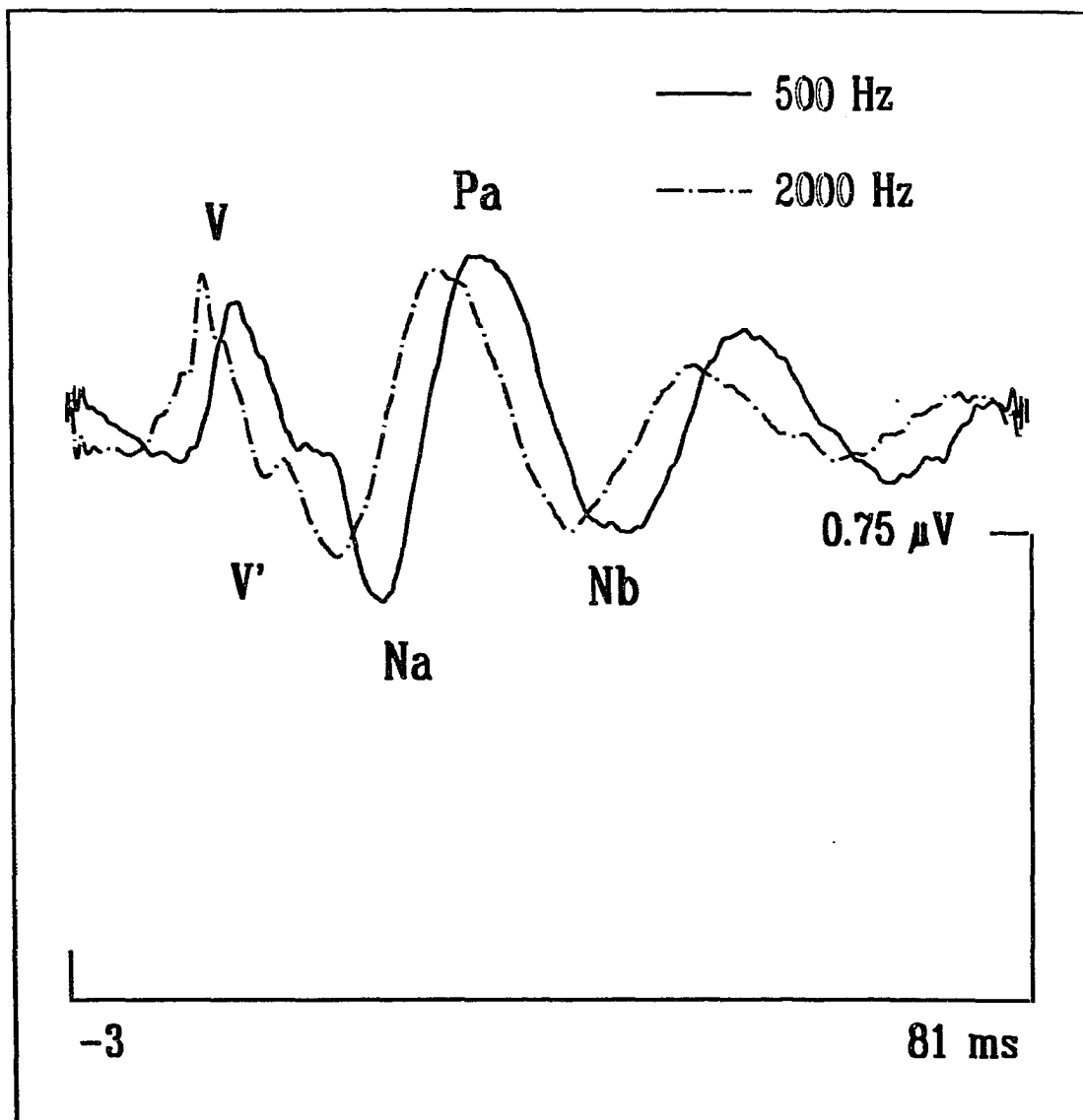


Figure 4. Grand mean (N=12) nonmasked ABRs and MLRs to 80 dB ppe SPL 500- and 2000-Hz (2-1-2 cycle) tones. Recordings are the average of 96,000 sweeps (8000 per subject).

The effects of natural sleep on the ABR and MLR have been studied by comparing the responses recorded during the various stages of slow-wave sleep and rapid eye movement sleep, as defined by the criteria of Rechtschaffen and Kales (1968), to those recorded while the individual is awake (Erwin and Buchwald, 1986; Mendel, 1974; Mendel and Goldstein, 1971; Osterhammel, Shallop, and Terkildsen, 1985). The results of these studies show no significant changes in the latency or amplitude of ABR wave V in the different stages of natural sleep. There are, however, marked latency and/or amplitude changes in MLR waves Pa and Nb as a function of sleep state. There is a significant prolongation of wave Nb latency in sleep stages 2-4 (Osterhammel et al., 1985) and the amplitude of waves Na-Pa and/or Pa-Nb decrease by approximately 40-50% in these later stages of sleep (e.g., Brown and Shallop, 1982; Mendel and Goldstein, 1971; Osterhammel et al., 1985). The influence of drug-induced sleep on these electrophysiologic responses has also been investigated. Chloral hydrate- or diazepam-induced sleep produce no significant changes in the amplitude or latency of either the ABR and/or MLR (Mendel, 1980; Özdamar and Kraus, 1983). Studies by C. Thornton and colleagues have shown that these two electrophysiologic responses are differentially affected by anaesthesia (Navaratnarajah, Thornton, Heneghan, and Jones, 1985; Thornton, Catley, Jordan, Lehane, Royston, and Jones, 1983; Thornton, Heneghan, James, and Jones, 1984; Thornton, Heneghan, Navaratnarajah, Bateman, and Jones, 1985; Thornton, Heneghan, Navaratnarajah, and Jones, 1985). Inhalation agents (e.g., halothane, isoflurane and enflurane) affect both the ABR and MLR, whereas intravenous agents (e.g., althesin and etomidate) affect only the MLR. These latency and amplitude changes are dependent on the dose of the

medication, and are reversible. It has been recommended that the middle latency response be recorded during optimal states of patient arousal due to the effects of sleep on the response (Kraus, McGee, and Stein, 1994). The differential effects of natural and drug-induced sleep on the ABR and MLR are most likely due to differences in the generators of these responses (Thornton et al., 1985).

The generators of the ABR have been investigated in humans (Durrant, Martin, Hirsch, and Schwegler, 1994; Hashimoto, 1982, 1984; Hashimoto, Ishiyama, Yoshimoto, and Nemoto, 1981; Martin, Pratt, and Schwegler, 1995; Møller and Janetta, 1982; Møller, Janetta, Bennett and Møller, 1981; Møller, Janetta, and Møller, 1982; Møller, Janetta, and Sekhar, 1988) and in animals (Achor and Starr, 1980; Jewett, 1970; Legatt, Arezzo, and Vaughan, 1986a,b), by making direct recordings from the VIIIth nerve, brain stem, thalamus, and cerebellum and cerebral cortices. Reviews of these studies by Legatt and colleagues as well as by Moore indicate that there are multiple generators for the majority of the vertex-positive peaks which comprise the "fast" components of the ABR (Legatt, Arezzo, and Vaughan, 1988; Moore, 1987). Wave I reflects the compound action potentials generated in the distal portion of the VIIIth nerve. Wave II and the negative peak located between waves I and II, known as wave In, are most likely stationary potentials which are generated as a result of physical changes that occur in the anatomical structures of the posterior fossa (Martin et al., 1995). Specifically, wave In is generated as the VIIIth nerve passes from the internal auditory canal into the cerebral spinal fluid and wave II is generated as the VIIIth nerve passes from the cerebral spinal fluid into the brainstem. Waves III and IV have their origin in the pons, with wave III reflecting axonal activity in the trapezoid body and the outflow of activity from the superior olivary complex, and wave IV representing

activity in the lateral lemniscus (Legatt et al., 1988; Moore, 1987). The origin of wave V is in the midbrain, in the region of the inferior colliculus. Wave V has a complex array of generators and predominately reflects activity in the lateral lemniscus and inferior colliculus (Durrant et al., 1994; Hashimoto, 1982; Legatt et al., 1988; Møller and Jannetta, 1982; Moore, 1987). The "slow" components of the ABR, in contrast, have their origin in the midbrain at the level of the inferior colliculus (Hashimoto, 1982; Legatt et al., 1988). It has been suggested that the slow wave predominately represents the summation of post-synaptic potentials within the inferior colliculus (Hashimoto, 1982; Legatt et al., 1988), whereas the "fast" waves are a reflection of action potentials within the VIIIth nerve and brainstem pathways (Legatt et al., 1988).

Several researchers have reported that the origin of the middle latency response is in the auditory cortex, as well as a possibility of subcortical involvement (Hashimoto, 1982; Kileny, Paccioretti, and Wilson, 1987; Özdamar and Kraus, 1983; Scherg and von Cramon, 1986; Vaughan and Ritter, 1970; Woods, Clayworth, Knight, Simpson, and Naeser, 1987). Applying modeling techniques, Scherg and von Cramon proposed that vertically oriented dipole sources located in both temporal lobes are the generators of the MLR (Scherg and von Cramon, 1986). Case studies on patients with lesions of the auditory cortex and thalamo-cortical pathways lend further support to a cortical origin for MLR waves Na, Pa, and Nb (Kileny et al., 1987; Scherg and von Cramon, 1986, Woods et al., 1987).

F1. Review of the Literature on ABRs to Tonal Stimuli

F1.A Effects of Stimulus Intensity

Decreasing the stimulus intensity results in an increase in the latency of wave V, as well as a decrease in the peak-to-peak amplitude of wave V-V' (Beattie and Boyd, 1985; Beattie and Kennedy, 1992; Davis, Hirsh, Turpin, and Peacock, 1985; Gorga, Kaminski, Beauchaine, and Jesteadt, 1988; Koderá, Yamane, Yamada, and Suzuki, 1977; Stapells and Picton, 1981; Suzuki et al., 1977; Suzuki, Koderá, and Yamada, 1984; Wu and Stapells, in preparation). This inverse relationship between wave V latency and stimulus intensity is present for all stimulus frequencies, however, the size of the latency increase is greater for the nonmasked lower versus higher frequency tonal stimuli. Wu and Stapells report that, when ABRs are recorded to nonmasked tonal stimuli, wave V mean latencies increase by approximately 5 ms for the 500-Hz tones and by 2.5 ms for the 2000-Hz tones as stimulus intensity is decreased from approximately 85 to 35 dB ppe SPL (Wu and Stapells, in preparation). The latency values from the data of Wu and Stapells are in overall agreement with those reported in the literature. Comparisons of the latency-intensity functions across studies, however, are complicated by differences in EEG band pass filters, slope of the filters, stimulus presentation rates, stimulus rise/fall times and stimulus intensities examined in these studies. Any one of these factors can individually or in combination affect the absolute latency and/or amplitude of the response, as will be discussed in further detail in this literature review.

The peak-to-peak amplitude of wave V-V' decreases significantly as stimulus intensity is decreased. The data of Wu and Stapells show decrements in the mean amplitude of wave V-V' of approximately 0.25 μ V

for responses to 2000-Hz tones and 0.40 μ V for responses to the 500-Hz tones as stimulus intensity is reduced from 85 to 25 dB ppe SPL (Wu and Stapells, in preparation).

A replicable wave V can be detected at stimulus intensities of 45-50 dB ppe SPL or less to 500-, 1000-, 2000- and 4000-Hz tonal stimuli presented in quiet or in notched noise masking in normal-hearing adults, young children, and infants (Beattie and Kennedy, 1992; Davis and Hirsh, 1979; Davis, Hirsh, and Turpin, 1983; Davis *et al.*, 1985; Gorga *et al.*, 1988; Koderer *et al.*, 1977; Purdy, Houghton, Keith, and Greville, 1989; Stapells, Gravel, and Martin, 1995; Stapells *et al.*, 1994; Stapells, Picton, Durieux-Smith, Edwards, and Moran, 1990; Suzuki *et al.*, 1977; Suzuki *et al.*, 1984).

F1.B Effects of Stimulus Frequency

Stimulus frequency has differential effects on the ABR. The auditory brainstem response to nonmasked high-frequency tones is similar in latency, amplitude and morphology to those evoked by clicks (Terkildsen, Osterhammel, and Huis in't Veld, 1973, 1975). An early study by Davis and Hirsh reported difficulty identifying ABRs recorded to low-frequency (500 Hz) stimuli (Davis and Hirsh, 1976). The authors hypothesized that the responses are probably mediated by the basal regions of the cochlea. Subsequent studies by Davis and Hirsh (1979) and others (e.g., Klein, 1983; Stapells and Picton, 1981; Suzuki *et al.*, 1977; Suzuki and Horiuchi, 1977) clearly demonstrated, however, that the ABR to 500-Hz stimuli is recognizable if the HP filter setting of the EEG is set lower than 50 Hz from the more conventional 100-150 Hz setting. The morphology of the response to 500-Hz tones is different from the responses to higher frequency tones, as shown in Figure 4. The earlier ABR waves are less recognizable and wave V has a broader

morphology and longer latency. Studies employing HP noise, notched noise, or white-noise masking have demonstrated that the increase in the latency of ABR wave V to the lower versus higher frequency tones reflects the longer travel time along the basilar membrane to reach the apical region of the cochlea (Beattie and Boyd, 1985; Beattie and Kennedy, 1992; Jacobson, 1983; Kileny, 1981; Laukli, 1983; Picton, Ouellette, Hamel, and Smith, 1979; Stapells, 1984; Stapells and Picton, 1981; Stapells et al., 1994, 1985). The longer wave V latency for the responses to the 500-Hz tones is also due to the longer rise time of the low-frequency stimulus (Jacobson, 1983; Koderá et al., 1977; Stapells and Picton, 1981).

F1.C Effects of EEG Band Pass Filtering

Knowledge of the spectral content of the ABR to tonal stimuli is necessary for the selection of appropriate HP filters for recording the response. The spectral content refers to the amount of energy as a function of frequency that is present in the electrical or output signal, which is the evoked potential. Several researchers have investigated the spectral content of the ABR at several stimulus intensities and have reported that frequencies below 250 Hz make the largest contributions to the ABR to both clicks and tonal stimuli (e.g., Elberling, 1979a,b; Suzuki, Sakabe, and Miyashita, 1982). At high stimulus intensities (i.e., approximately 105 dB ppe SPL), half of the energy of the ABR to click and tonal stimuli is located below 110 Hz, and for low stimulus intensities (i.e., 35 dB ppe SPL), half of the stimulus energy occurs below 90 Hz (Elberling, 1979a,b; Suzuki et al., 1982). In response to high stimulus intensities, there are also peaks of energy in the ABR to clicks and tonal stimuli in the frequency regions of approximately 400-600 Hz and 900-1100 Hz. These higher frequency

regions contribute to the fast waves in the ABR and significantly decrease or disappear as stimulus frequency and/or intensity is decreased. Thus, any HP filtering in the frequency range below 250 Hz may cause decreases in the amplitude of the ABR and should be considered carefully.

Suzuki and Horiuchi investigated the effects of EEG HP filtering on the ABR to 500-, 1000-, 2000-, and 4000-Hz tonal stimuli, and report that the amplitude of wave V decreases when the HP cutoff frequency is increased from 50 to 200 Hz (Suzuki and Horiuchi, 1977). This effect occurs at all frequencies but is particularly evident in the responses to 500-Hz tones, as the primary frequency component of the response to the 500-Hz tones is lower than that in response to higher frequencies. Specifically, these authors report that HP filter settings of 50, 100, and 200 Hz results in mean amplitude attenuations of approximately 3, 7 and 10.5 dB in response to the 500-Hz stimuli, and 0.4, 3, and 6 dB for the responses to the 2000- and 4000-Hz stimuli. The effects of varying the EEG HP filter settings and rolloff slopes on the ABR to 500-Hz tones were further investigated by Stapells and Picton (1981) and by Hyde (1985). Both studies report that the latency of wave V and the amplitude of wave V-V' decreases as the HP cutoff frequency is increased from 10 to approximately 200 Hz. Specifically, the data of Stapells and Picton show that the mean wave V latency to a 110 dB peak SPL 500-Hz tone decreases from approximately 8.51 ms to 8.3 ms as the HP cutoff filter is increased from 10 to 100 Hz (12 dB/octave), with the mean amplitude decreasing from approximately 0.48 to 0.20 μ V (Stapells and Picton, 1981). These latency and amplitude changes are due to the removal of the low-frequency electrical energy present in the response and these effects are greater the higher the rolloff slope of the filter (e.g., 48

dB/octave versus 6 dB/octave). There are significant changes in the morphology of the ABR as the rolloff slope is increased, especially in response to low-frequency tonal stimuli. These investigators report that the largest brainstem response to a 500-Hz tone is recorded using a HP filter setting of 10 Hz combined with a low rolloff slope, i.e., 6-12 dB/octave (Stapells and Picton, 1981). If a 10-20 Hz HP EEG setting and a low-rolloff slope is employed, the response to a 500-Hz tone is a broad vertex-positive wave that can be recorded down to within 10-20 dB of threshold.

Davis and Hirsh, employing a 40-Hz HP filter with a 24 dB/octave slope, report that the main component of the response to a 500-Hz tone is a vertex-negative wave which they labeled as the "slow-negative wave at 10 ms" or SN10 (Davis and Hirsh, 1979). The studies by Stapells and Picton and by Hyde demonstrated that the use of the 40-Hz HP filter setting combined with a high-rolloff slope (24 dB/octave) decreases the amplitude and distorts the response to the 500-Hz tone, emphasizing the vertex-negative wave (V') following wave V (Hyde, 1985; Stapells and Picton, 1981).

F1.D Effects of Stimulus Rate

An increase in stimulus presentation rate results in an increase in wave V latencies to tonal stimuli (Kodera, Yamada, Yamane, and Suzuki, 1978; Stapells and Picton, 1981). The data of Stapells and Picton show that mean wave V latencies to 110 dB peak SPL 500-Hz tones (10 Hz; 6 dB/octave filter) are 8.50, 9.50 and 9.56 ms for stimulus presentation rates of 10, 20 and 35/s (Stapells and Picton, 1981).

There are no significant changes in the amplitude of wave V-V' with increases in stimulus presentation rate from approximately 10 to 25/s (Davis and Hirsh, 1979; Kodera et al., 1978; Stapells and Picton,

1981). At stimulus presentation rates of approximately 30 to 35/s, however, there is a slight increase in the amplitude of wave V-V' (Kodera et al., 1978; Stapells and Picton, 1981). In the study by Stapells and Picton, the largest wave V-V' amplitude for the 500-Hz tone (110 dB peak SPL) is recorded using a combination of a stimulus presentation rate of 35/s and a 10 Hz (6 dB/octave) HP filter setting (Stapells and Picton, 1981). These authors conclude that the enhancement in wave V-V' amplitude present at this higher stimulus rate (35/s) is most likely due to superimposition of the MLR on the earlier ABR (Stapells and Picton, 1981). This topic will be discussed below in further detail in the middle latency response section of this literature review.

F1.E Effects of Stimulus Rise Time

The amplitude of the ABR wave V-V' to tonal stimuli decreases with increases in rise time (Jacobson, 1983; Kodera, Yamane, Yamada, and Suzuki, 1977; Kodera, Marsh, Suzuki, and Suzuki, 1983; Stapells and Picton, 1981). The major changes in amplitude for the responses to the 500- to 4000-Hz tonal stimuli occur when rise times exceed 5 ms (Stapells and Picton, 1981). This inverse relationship between response amplitude and rise time is evident at all stimulus intensities (Kodera et al., 1983; Stapells and Picton, 1981).

Several investigators have shown that increases in the rise time of tonal stimuli yield a significant increase in wave V latency (Jacobson, 1983; Kodera et al., 1977; Stapells and Picton, 1981). In 1979, Brinkmann and Scherg proposed a concept known as "virtual trigger time" (VTT), which represents the point on the rise time of the stimulus when the majority of individual nerve fibers contributing to the response are activated (Brinkmann and Scherg, 1979). Brinkmann and

Scherg report that VTT is a function of both the rise time and intensity of the stimulus. A subsequent study by Stapells and Picton, demonstrated that VTT is also a function of stimulus frequency, as their data show that the increases in wave V latency seen with increases in rise time are greater for low- versus high-frequency tonal stimuli (Stapells and Picton, 1981). This differential frequency effect may be due to the phase-locking properties of the low-frequency auditory nerve fibers (Stapells and Picton, 1981). Nerve fiber activation for low-frequency stimuli is locked to stimulus phase, thus, increasing stimulus rise time could delay the firing of the majority of these nerve fibers by one or more cycles. This delay would be more pronounced as the frequency of the stimulus is lowered (Stapells and Picton, 1981).

A question concerning rise time that has been investigated by several researchers is: "What portion of the stimulus is most effective in eliciting the response"? This question is important in determining if there are optimal rise/fall times for recording evoked potentials to various stimuli. One method that has been used to investigate this issue has been to vary the rise time of the stimulus while keeping the slope of the rise constant. This approach eliminates the possible confounding effects of slope of the rise time on the amplitudes and latencies of the response. Suzuki and Horiuchi, in a constant rise-time study, tested seven adult humans with normal hearing and employed changes in latency and response detectability of the ABR to 500- and 2000-Hz stimuli to determine which portion of the stimulus is most effective in eliciting the ABR (Suzuki and Horiuchi, 1981). These investigators report no significant change in the latency of the response to 76 dB ppe SPL 2000-Hz tones when rise times are increased beyond 0.5 ms (first cycle), whereas for lower stimulus intensities, the latency of the response increases with increasing rise times up to 1.5 ms (Suzuki and Horiuchi,

1981). The latencies of the ABR to the 500-Hz tones, however, are more variable than the responses to the 2000-Hz stimuli. Suzuki and Horiuchi also report little difference in the 500-Hz response detectability for rise times between 3 and 10 ms. Based on the changes in latency and response detectability, they conclude that the initial 3 cycles of the 2000-Hz tone and the first 1.5 cycles of the 500-Hz tone are the essential portions of the stimulus that evoke the ABR (Suzuki and Horiuchi, 1981).

Kodera and colleagues, in a constant-slope rise time study on cats, employed a different criterion (i.e., changes in ABR wave V amplitude as a function of rise/fall time) in order to determine this effective area (Kodera et al., 1983). The results of this study demonstrate that the amplitude of wave V increases with increases in rise time up to a critical point after which further increases in rise time result in either no change or a decrease in amplitude. Based on these findings, Kodera and colleagues concluded that the effective portion of the tone is the initial 2 to 4 cycles for the 500-Hz stimuli and the initial 4 to 8 cycles for 2000-Hz tones (Kodera et al., 1983). The combined results of the Suzuki and Horiuchi study and the Kodera et al. study seem to suggest that there is an "effective portion or duration" of the tone which elicits the ABR (Kodera et al., 1983; Suzuki and Horiuchi, 1981). The number of cycles in this critical duration appears to be dependent on both the stimulus frequency and intensity. Further research to better define this issue is in progress at the time of this writing (Lichtenstein and Stapells, 1995).

Several questions arise when determining the optimal rise time settings for recording the ABR to tonal stimuli. The first is: "Is it better to use a tonal stimulus with a rise time consisting of a constant

number of cycles or a rise time which has a constant duration, regardless of stimulus frequency?" Takagi and co-workers investigated this question by recording ABRs to tonal stimuli, presented at approximately 65-70 dB ppe SPL, using two rise/fall conditions: (1) a 2 cycle rise/fall time with no plateau (2-0-2); and (2) a 4-ms rise/fall time with no plateau (Takagi et al., 1985). These researchers studied the changes in wave V latency and amplitude as a function of stimulus frequency for each rise/fall condition. They reported that the latency of wave V for both the slow and fast components increases with a decrease in stimulus frequency and the latencies of both components are longer for the constant rise/fall condition versus the constant cycle condition (Takagi et al., 1985). For the stimuli with a constant rise/fall time, the amplitude of the slow component decreases with increasing frequency, while amplitude of the fast component remains stable. In contrast, when tonal stimuli with 2-0-2 cycles are used, the amplitude of the slow component is unchanged across frequency while a decrease in the amplitude of the fast component is seen with decreasing stimulus frequency. For each stimulus frequency, the decrease in amplitude of the slow component for constant rise/fall tones is greater than the decrease in amplitude for the fast component in response to the 2-0-2 tones. Therefore, the amplitude of the wideband ABR (fast + slow) is larger across frequencies for tones with a constant rise/fall cycles versus those with a constant rise/fall time. Takagi and colleagues recommend the use of rise times consisting of a constant number of cycles rather than a constant duration because there are smaller differences in the amplitude of the slow component across frequencies using the constant cycles (Takagi et al., 1985).

A second related question is: "How many cycles of the tone can be included in the rise time of the stimulus without causing a significant reduction in response amplitude?" Tones with longer rise times have greater acoustic frequency specificity (Burkard, 1984; Gorga and Thornton, 1989; Jacobson, 1983; Stapells and Picton, 1981), however, when rise times exceed 5 ms there are significant decreases in wave V amplitude (Stapells and Picton, 1981). Therefore, significant decreases in wave V amplitude for a 500-Hz tone would occur if rise times of greater than 2 to 2.5 cycles were used. The use of 2 to 2.5 cycle rise times are also supported by the findings of Kodera and co-workers on the effective portions of the tone contributing to the response (Kodera et al., 1983).

Another question related to the duration of the tonal stimuli has been: "Is there an optimal number of cycles for the plateau portion of the tone which provides the most frequency-specific ABR thresholds?" Davis and colleagues conducted a preliminary investigation of this issue by using three sets of tones each having linear rise and fall times equaling 2 cycles and plateaus equalling either 0, 1, or 10 cycles (Davis, Hirsh, Popelka, and Formby, 1984). These tone patterns were referred to as "2-0-2", "2-1-2", and "2-10-2" tones. The 10 cycle plateau is not a feasible option for recording ABRs as it extends beyond the effective duration of the stimulus contributing to the response (Kodera et al., 1983), however, it was included as a possible option for recording frequency-specific MLRs. Davis and co-workers compared the behavioral thresholds measured to these three sets of tones in their normal-hearing and hearing-impaired subjects (Davis et al., 1984). The normal-hearing subjects have lower thresholds (3 dB) for the "2-1-2" versus "2-0-2" tones. The average thresholds for the "2-1-2" and "2-0-2" tones are similar in hearing-impaired subjects with relatively flat

audiograms. Results for subjects with very steep high-frequency hearing losses (i.e., > 25 dB/octave), however, indicate both sets of tones underestimate the degree of the pure-tone hearing loss, with the "2-0-2" tone providing the least sensitive measure. The use of "2-1-2" tones has been recommended for frequency-specific ABR testing as the best possible compromise between duration and frequency specificity based on their better threshold sensitivity and the limitations imposed by effective duration of the stimuli for ABR (Davis, 1976; Davis et al., 1984). Subsequent studies have shown that "2-1-2" tones presented in either quiet or in the presence of HP and/or notched noise provide frequency-specific ABR thresholds in normal and hearing-impaired adults, young children, and infants (e.g., Munnerley, Greville, Purdy, and Keith, 1991; Purdy et al., 1989; Stapells, 1984, 1989; Stapells et al., 1990; 1995).

F1.F Effects of Stimulus Temporal Shaping

Dolan and Klein investigated the effects of temporal shaping of tonal stimuli on the frequency specificity of gerbils' VIIIth-nerve compound action potentials (CAP), as measured by tuning curves (Dolan and Klein, 1987). The nonlinear stimulus employed in their study was a 1/4-sine-gated signal. The authors report that the CAP tuning curves for responses to the linear and nonlinear envelopes are similar and equally frequency specific for all the frequencies tested (i.e., 1000, 4000 and 8000 Hz) at the lower probe level (40-50 dB SPL) and for 1000- and 4000-Hz tones at a higher probe level (70-75 dB SPL). There is a difference in the responses to the two temporal envelopes, however, for the higher intensity 8000-Hz probes. Specifically, the authors report a downward shift of the tuning-curve tips to frequencies below 8000 Hz for both envelopes, with the frequency displacement being greater for the linear-

gated signal. If it is assumed that there is a direct relationship between the frequency of the tuning-curve tip and the characteristic frequency (CF) of the fibers that dominate the CAP, this finding suggests that, at high intensities, the 8000-Hz linear-gated tone produces responses that are more "off-frequency" than the response obtained with the nonlinear envelope (Dolan and Klein, 1987). However, there are no differences in the frequency specificity of the responses for the linear versus nonlinear 1000- and 4000-Hz stimuli.

In an unpublished study, Purdy and Abbas assessed the effects of stimulus temporal shaping on the frequency specificity of the ABR in humans (Purdy and Abbas, 1989). They studied, in normal-hearing subjects and in subjects with steep-sloping high-frequency sensorineural hearing losses, ABR thresholds for nonmasked 1000-, 2000- and 4000-Hz tones gated with exact-Blackman or linear windows. The authors report that, despite the spectral differences between the stimuli, there are no significant differences between the exact-Blackman- or linear-gated tones in terms of how well the ABR thresholds predict pure-tone thresholds. The majority of the threshold predictions (86%) for these nonmasked stimuli were within 15 dB of the subjects' actual pure-tone audiometric thresholds. This close correspondence between ABR thresholds and behavioral thresholds is in agreement with the accuracy (i.e., 2-30 dB) of threshold prediction demonstrated using either the HP noise masking/derived response technique (Don, Eggermont, and Brackmann, 1979; or the notched-noise masking technique (Munnerley et al., 1991; Picton et al., 1979; Stapells, 1984; Stapells et al., 1995, 1990). For those few cases in which the nonmasked-ABR threshold either under or overestimated the pure-tone behavioral threshold, the prediction of threshold is equally in error for the linear and nonlinear stimuli. For example, Purdy and Abbas report an underestimation of the 4000-Hz

audiometric threshold by 25 dB in a subject who had a precipitous high-frequency hearing loss (i.e., a 45 dB drop between 3000 and 4000 Hz). The predicted ABR threshold at 4000 Hz was 40 dB HL for both the exact-Blackman- and linear-gated tones (Purdy and Abbas, 1989). The underestimation of thresholds in this subject is most likely due to acoustic splatter of the 4000-Hz tones to the more sensitive 2000-3000 Hz region and thus reinforces the need for noise masking to improve the frequency specificity of these responses.

Robier, Fabry, Leek, and Van Summers (1992) investigated whether there are wave V latency differences in normal-hearing and hearing-impaired subjects to 500-Hz tonal stimuli gated with five different windowing functions (i.e., linear, Blackman, Hamming, Hanning, and cosine). The frequency specificity of the ABR can be assessed by comparing the differences in wave V latencies recorded to the same stimulus in normal versus hearing-impaired subjects. All of the hearing-impaired subjects in this study had normal-hearing sensitivity from 500 through 2000 Hz with at least a moderate high-frequency sensorineural loss at 4000 Hz (Robier et al., 1992). The frequency specificity of the ABR to these various temporal stimuli, however, was not adequately assessed in this study because the hearing loss of the subjects was at least two octaves away from the 500-Hz stimulus frequency. It is therefore not surprising that Robier and co-workers report no significant differences in wave V latencies between their normal and hearing-impaired subjects, nor any significant differences among the responses to the five stimuli (Robier et al., 1992).

There have been suggestions by some investigators that, based on the spectral differences between these two envelopes, a Blackman-gated stimulus should provide a more frequency-specific response than a linear-gated stimulus (Gorga et al., 1992; Gorga and Thornton, 1989;

Telian and Kileny, 1989). The existing data concerning this issue do not support this conclusion but there have been few studies and further investigation is needed.

F1.G Use of Masking

There are two primary purposes for using masking with the auditory brainstem response: (1) to use noise-masking techniques to improve the frequency specificity of the response, and (2) to use noise-masking techniques to specifically investigate the frequency specificity of responses to various stimuli. The following is a discussion of these two goals and the types of masking techniques that can be used to achieve these goals.

F1.G1 Masking to improve the frequency specificity of the ABR

Several noise-masking techniques (e.g., HP noise, notched noise, broadband "white" noise masking) have been proposed to improve the frequency specificity of the nonmasked response to tonal stimuli at higher stimulus intensities (i.e., > 70 dB ppe SPL). The purpose of HP masking is to prevent the contributions of high-frequency fibers to the response without affecting fibers with characteristic frequencies below the HP cutoff frequency. The use of HP noise masking with moderate and high intensity low-frequency tonal stimuli (i.e., 500 and 1000 Hz) yields longer latencies in comparison to the nonmasked response (Beattie and Kennedy, 1992; Burkard and Hecox, 1983; Jacobson, 1983; Kileny, 1981; Laukli, 1983; Laukli, Fjermedal, and Mair, 1988). This change in latency reflects the removal of the high-frequency contributions to the response and the longer travel time to the apical region of the cochlea. The HP noise masking technique has been shown to give reliable estimates of hearing sensitivity at 500 Hz in both normal and hearing-impaired

subjects (Kileny, 1981; Munnerley et al., 1991; Purdy et al., 1989). The disadvantage with HP-masking noise is that it is inappropriate for middle- and high-frequency tones, as it does not prevent the spread of energy to frequencies below the nominal test frequency. This can result in underestimation of degree of hearing loss at that nominal frequency due to the contribution from more sensitive lower-frequency regions, as was the case in the example of the underestimation of threshold at 4000 Hz described from the Purdy and Abbas (1989) study. To prevent this problem, it has been recommended that notched noise masking be used (Picton et al., 1979).

Notched noise is broadband noise in which a band of frequencies has been stopped or rejected. The purpose of notched noise masking is to prevent both high- and low-frequency regions of the cochlea, away from the nominal test frequency, from contributing to the response (Beattie and Boyd, 1985; Beattie and Kennedy, 1992; Beattie and Spence, 1991; Laukli, 1983b; Munnerley et al., 1991; Picton et al., 1979; Purdy et al., 1989; Stapells and Picton, 1981; Stapells et al., 1995, 1994, 1990, 1985). The responsive region of the cochlea is therefore limited to the frequencies within the notch. The notched noise technique has been shown to give reliable estimates of the 500-, 1000-, 2000-, and 4000-Hz pure-tone behavioral thresholds (i.e., to within 10-20 dB) in most hearing-impaired subjects (Munnerley et al., 1991; Picton et al., 1979; Stapells, 1984; Stapells et al., 1995, 1994, 1990, 1985).

A third suggestion to improve the frequency specificity of the nonmasked responses has been the use of broadband "white" noise masking. The advantage of this type of noise is that it requires less complex instrumentation and calibration than HP and/or notched noise. Several investigators have shown that the use of white noise provides approximately the same frequency specificity as notched noise (Beattie

and Boyd, 1985; Picton et al., 1979; Stapells, 1984). The use of white noise, however, results in lower response amplitudes compared to notched noise (Picton et al., 1979; Stapells, 1984). Picton and colleagues demonstrated that when a 97 dB ppe SPL 500-Hz tone is presented in the presence of 90 dB SPL white noise and/or notched noise, the wave V-V' amplitude is 0.39 μ V for the white noise and 0.61 μ V for the notched noise (Picton et al., 1979).

F1.G2 Masking to investigate the frequency specificity of ABRs to different stimuli

Noise masking may also be used to investigate the frequency specificity of electrophysiologic responses to different stimuli. The masking techniques that have been used to investigate the frequency specificity of the auditory evoked potentials include: pure-tone masking, notched noise masking, and the HP noise/derived response (HP/DR) technique. Pure-tone masking has been used to investigate the frequency specificity of the ABR to brief tones (Folsom, 1984; Folsom and Wynne, 1987; Klein, 1983; Klein and Mills, 1981a,b; Mackersie et al., 1993; Wu and Stapells, 1994). Klein used a simultaneous pure-tone masking paradigm to investigate the frequency specificity of the slow-wave component of the ABR to 250-, 500-, 1000-, 2000- and 4000-Hz tones with 3 ms rise/fall times (Klein, 1983). Specifically, he measured the level of pure-tone masking needed to reduce the amplitude of the slow-wave component by half. These measurements provided an inverse estimate of the amount of energy in the brief tone that was contributing to the response at each of the pure-tone masker frequencies. Klein reported that the slow-wave component of the ABR is reasonably frequency specific for all the tonal stimuli up to 77 dB ppe SPL, with the exception of responses to 250-Hz tones, which demonstrated poor frequency specificity

(Klein, 1983). A stimulus presentation rate of 40/s was employed in this study and therefore the slow-wave responses recorded may be contaminated by the 40-Hz response (to be discussed in further detail in the MLR section of this review). The studies by Mackersie et al. and Wu and Stapells demonstrated good frequency specificity for the ABR to 10/s low-intensity (60 dB ppe SPL) 500- and 2000-Hz tones (Mackersie et al., 1993; Wu and Stapells, 1994). Folsom investigated the changes in the latency and amplitude of wave V produced by pure-tone masking, and reported that the ABRs to 75 dB ppe SPL 1000- and 4000-Hz filtered clicks (which were equivalent to tonal stimuli having approximately 3 cycle rise/fall times and 1 cycle plateaus) show good frequency specificity (Folsom, 1984). When these same stimuli are presented at 95 dB ppe SPL, however, there is a spread of excitation to the higher-frequency regions of the cochlea and thus a decrease in the frequency and place specificity of the response.

A comparison of the nonmasked tonal response to the response obtained to the same signal in the presence of notched noise masking is a second method that has been used for investigating the frequency specificity of the ABR to tonal stimuli. Several researchers have shown that notched noise masking significantly increases the latency and decreases the amplitudes of ABR wave V to tonal stimuli at stimulus intensities of greater than 70 dB ppe SPL (Beattie and Kennedy, 1992; Jacobson, 1983; Picton et al., 1979; Stapells, 1984; Stapells and Picton, 1981). At these high stimulus intensities, the response to the nonmasked tones are mediated, in part, by regions of the cochlea outside of the nominal stimulus frequencies. The changes in wave V latency for the response recorded in notched noise are most evident for the responses to 500-Hz tones compared to the responses to 2000-Hz tonal stimuli because the latency of the response to a nonmasked high-

intensity 500-Hz tonal stimulus is mainly determined by higher frequency regions of the cochlea. The notched noise masks out the response from these higher frequency regions, leaving a response with a longer latency reflecting the travel time to the apical region. For the response to the 2000-Hz tones, significant increases in latencies for the responses in notched noise occurred for the 1 and 2 ms rise-time conditions only (Stapells and Picton, 1981). These authors suggested several reasons why the notched noise masking had less of an effect on the latencies of the responses to the high-frequency tones compared to the responses to the low-frequency tones. First, the 2000-Hz tones had better acoustic frequency specificity compared to the 500-Hz tones as the rise times of the tonal stimuli had a constant duration expressed in ms. Secondly, cochlear contributions to the response from more basal regions of the cochlea produce very small changes in the response latencies to the 2000-Hz tones due to the better neural synchrony of the higher frequency regions of the cochlea. Finally, the speed of the travelling wave is faster for the higher *versus* lower frequency regions of the basilar membrane, thus decreasing the latencies of the responses to the former (Stapells and Picton, 1981). The amplitudes, however, of the responses to high-intensity tonal stimuli presented in notched noise were reduced for both stimulus frequencies because the masking eliminated the contributions from frequency regions above and below the notch (Stapells and Picton, 1981).

A disadvantage of the notched noise technique is that of the spread of masking into the notch, especially from the low-frequency edge. Picton and co-workers report that when employing filters with slopes of 48 dB/octave, the effective depth of the notch is reduced to approximately 27 dB by the spread of masking from the low-frequency edge (Picton et al., 1979). This spread of masking is greater at higher

intensities (Egan and Hake, 1950), which are often the levels at which the ABR evaluations are conducted. Upward spread of masking may be even more pronounced in patients with sensorineural hearing loss, as indicated by the differences in the shape of the low-frequency tails of tuning curves in individuals with sensorineural hearing losses compared to normal-hearing subjects (e.g., Liberman, 1984; Liberman and Kiang, 1978; Kiang, Liberman, Sewell, and Guinan, 1986). The less-steep tails of the tuning curves in these hearing-impaired individuals indicate that they are susceptible to a greater spread of masking from the low-frequency edge of the notched noise (Eggermont, 1977; Trees and Turner, 1986).

F1.B Effect of Stimulus Intensity on the Frequency Specificity of the ABR

Brainstem responses in normal-hearing subjects to 500-, 1000-, 2000-, and 4000-Hz tones are frequency specific when the tones are presented at low to moderate intensities, i.e., 67 dB ppe SPL or less (Beattie and Kennedy, 1992; Jacobson, 1983; Klein, 1983; Mackersie et al., 1993; Picton et al., 1979; Stapells and Picton, 1981; Wu and Stapells, 1994). When testing at stimulus intensities of greater than 70 dB ppe SPL, however, there can be contributions to the response from frequencies either above or below the test frequency due to the spread of energy from the test tone to more sensitive regions of the cochlea (Beattie and Kennedy, 1992; Burkard and Hecox, 1983; Jacobson, 1983; Klein, 1983; Picton et al., 1979; Stapells and Picton, 1981). This stimulus intensity effect is due both to the upward spread of cochlear excitation which occurs with an increase in stimulus intensity, as demonstrated, for example, by VIIIth nerve tuning curve studies (e.g.,

Rose *et al.*, 1971), and to the effects of spectral splatter. That is, the spectrum of the stimulus is broad and the cochlear excitation pattern is even broader.

The poorer frequency and place specificity of the ABR to high-intensity nonmasked tonal stimuli has been demonstrated by using several masking techniques (i.e., pure-tone masking, HP noise, and notched noise). Each of these masking techniques is described in further detail in the masking section of this literature review. Klein, employing a pure-tone masking paradigm, demonstrated that there are changes in the tuning properties of the slow-wave component of the ABR to tonal stimuli (3 ms rise/fall time) presented at higher (77 dB ppe SPL) intensities compared to responses to lower (≤ 67 dB ppe SPL) stimulus intensities (Klein, 1983b). At 77 dB ppe SPL, the tips of the tuning curves to the 500- and 1000-Hz tones become broader, suggesting a decrease in the frequency specificity of the responses due to the increased contributions from the surrounding frequency regions. The slow-wave responses to the 250-Hz tones exhibit relatively poor frequency tuning (i.e., the tips of the tuning curves are in the 350-400 Hz region) at both low and high stimulus intensities. The tuning properties of the slow-wave response to higher-frequency (e.g., 2000 and 4000 Hz) tonal stimuli were also investigated, however, the highest stimulus intensity employed with these stimuli was 67 dB ppe SPL (Klein, 1983).

Several investigators have compared tonal ABRs recorded in quiet to those recorded in either HP noise and/or notched noise for stimulus intensities of greater than 70 dB ppe SPL (Beattie and Kennedy, 1992; Burkard and Hecox, 1983; Jacobson, 1983; Picton *et al.*, 1979; Stapells, 1984; Stapells and Picton, 1981). These studies report increases in the latency and decreases in the amplitude of wave V for the masked responses compared to the nonmasked responses. The changes in response

amplitude and latencies produced by the noise masking led these researchers to conclude that ABRs to high-intensity nonmasked tones contain contributions to the response from frequencies away from the nominal frequency and thus have reduced frequency specificity (Beattie and Kennedy, 1992; Burkard and Hecox, 1983; Jacobson, 1983; Picton *et al.*, 1979; Stapells, 1984; Stapells and Picton, 1981). This is especially true for responses to high-intensity low-frequency stimuli.

The poorer frequency specificity of the ABR to high-intensity tonal stimuli may have particularly detrimental effects when trying to estimate hearing thresholds in hearing-impaired subjects. If large differences in threshold sensitivity are present across frequencies, an underestimation of ABR threshold can occur due to contributions from more sensitive areas of the cochlea. In practice, this problem may occur more frequently when assessing high-frequency (e.g., 4000 Hz) thresholds in individuals who have normal low-frequency hearing and a steep high-frequency hearing loss (Davis *et al.*, 1984; Hayes and Jerger, 1982; Picton, 1978; Picton *et al.*, 1979; Purdy and Abbas, 1989; Stapells, 1984; Stapells *et al.*, 1994, 1990, 1985), but can also occur with individuals who have a reverse-slope or notched audiogram (Hayes and Jerger, 1982; Picton *et al.*, 1979).

F1.I Problems with the 500-Hz ABRs

An area that has raised some concern for clinical application of the ABR has been the identification and threshold sensitivity of responses originating from the 500-Hz cochlear region (Beattie and Spence, 1991; Don *et al.*, 1979; Laukli, 1983b; Laukli *et al.*, 1988; Stapells, 1984). The problems that have arisen can be broken down into several areas. Each of these areas will be discussed in further detail.

Fl.II ABRs to clicks that have been masked with 500-Hz HP noise

Beattie and Spence reported that only half of their normal-hearing subjects had identifiable ABRs to clicks presented at 95 dB ppe SPL when masked by 500-Hz HP noise (Beattie and Spence, 1991). Very few, if any, of their subjects have responses at lower intensities. These authors conclude that presenting clicks in the presence of 500-Hz HP noise is of limited value in assessing low-frequency hearing sensitivity due to the high thresholds (i.e., 95 dB ppe SPL) for their normal-hearing subjects and to the high intensities required to mask the clicks. In contrast, Stapells (1984) was able to record an ABR from all of his normal-hearing subjects to 100 dB ppe SPL clicks in 500-Hz HP noise masking. The responses consisted of a broad and delayed wave V that could be recorded down to approximately 70 dB ppe SPL or lower in the HP noise, thus showing a larger range of hearing levels that can be assessed with this technique. The use of click stimuli in the presence of 500-Hz HP noise, however, has not been recommended as an optimal method of assessing low-frequency threshold sensitivity due to the high intensity levels of HP noise required to adequately mask the click stimulus (Stapells, 1984; Stapells *et al.*, 1994, 1985). Low-frequency tonal stimuli, on the other hand, are more frequency specific than the broad-spectrum clicks, and ABRs to high-intensity 500-Hz tonal stimuli may be masked by HP noise set at a substantially lower intensity. The level of HP noise needed to mask high-intensity ABRs to 500-Hz tonal stimuli is lower than for click stimuli because one only needs to mask the sidelobes of high-frequency energy in the tones which are approximately 30 dB lower than the intensity of the high-frequency energy present in the click stimulus.

F1.I2 500-Hz ABR derived responses using clicks

The 500-Hz derived response ABR to a click stimulus can only be detected down to approximately 60-65 dB ppe SPL in normal-hearing subjects (Don et al., 1979; Stapells, 1984). Given the high levels of masking noise required to adequately mask a click stimulus, the range of hearing losses that can be estimated for the 500-Hz region using a click stimulus is therefore limited.

F1.I3 ABRs to 500-Hz tonal stimuli that have been masked with HP noise

Laukli and colleagues reported that the use of HP masking noise with a 500-Hz tonal stimulus significantly "distorted" waveform quality, making the identification of wave V problematic (Laukli, 1983b; Laukli et al., 1988). When they could identify the low-frequency response, the thresholds were quite variable, and only 3 of 18 ears had 500-Hz thresholds below 95 dB ppe SPL (Laukli et al., 1988). Many other researchers, however, have been able to record replicable and clearly identifiable responses to 500-Hz stimuli in the presence of HP and/or notched-noise masking down through 55 dB ppe SPL or lower (e.g., Hyde, 1985; Hyde, Matsumoto, and Alberti, 1987; Jacobson, 1983; Kileny, 1981; Munnerley et al., 1991; Purdy et al., 1989; Stapells and Picton, 1981; Stapells et al., 1995, 1994, 1990). Possible explanations for Laukli and colleagues' poor results could be the high background electrical noise levels present in their surgical testing suite and/or the high masking-noise levels employed in their studies.

Several studies have compared the ABR to 500-Hz tones in a quiet condition to its presence in either HP and/or notched noise (Hyde, 1985; Jacobson, 1983; Kileny, 1981; Picton et al., 1979, Picton, Stapells, and Campbell, 1981; Purdy et al., 1989; Stapells, 1984; Stapells and Picton,

1981; Stapells et al., 1994, 1985). All of these studies report a broad wave V present in the noise conditions. The latency of the wave V in the noise masking paradigms is substantially longer than for the quiet condition, independent of stimulus rise time or intensity. The longer latency reflects the travel time along the basilar membrane to the apical regions of the cochlea. The amplitude of wave V is reduced in the noise conditions versus the quiet condition. The amplitude changes are the greatest at the higher stimulus intensities and reflects the masking of contributions to the response from frequencies other than the nominal test frequency. Therefore, the recording of ABRs to 500-Hz tonal stimuli in the presence of either HP and/or notched noise masking is an effective means of assessing low-frequency threshold sensitivity.

F1.I4 Responses underlying the waveforms to 500-Hz tones: ABR versus MLR

When ABRs and MLRs are recorded to low-frequency tones, the spectral content of the responses are similar. If the ABR is recorded at a stimulus presentation rate of approximately 40/s, there may be an overlapping of the MLR with the ABR, (which will be discussed in further detail in the MLR section) which may lead to questions concerning whether the response is ABR, MLR, or a combination of both. In 1982, Eysholdt and Schreiner reported on a technique known as maximum length sequences (MLS) which may be used to eliminate the overlapping of these electrophysiologic responses. In this technique, pseudorandom pulse trains, called maximum length sequences, are used as the stimuli (Eysholdt and Schreiner, 1982). Cross correlation analysis is used to disentangle the responses.

Picton and colleagues compared ABRs obtained to 500- and 2000-Hz brief tones elicited with conventional averaging techniques (40/s rate) to those obtained using MLS analysis (Picton, Champagne, and Kellett, 1992). These authors suggested that the evoked potential to a 40-Hz stimulus recorded with conventional averaging is a combination of ABR and overlapping MLR. Picton *et al.* and others have shown that the response to a 40-Hz stimulus may be recorded to within 10 dB of the mean behavioral thresholds for the 500- and 2000-Hz tones (e.g., Brown and Shallop, 1982; Galambos, Makeig, and Talmachoff, 1981; Picton *et al.*, 1992; Stapells, Linden, Suffield, Hamel, and Picton, 1984). When the MLS technique is employed, the mean thresholds for the ABR and MLR time windows to 2000-Hz tones are 39 and 35 dB ppe SPL respectively. In contrast, the mean MLS thresholds for the 500-Hz tones are 57 dB ppe SPL for the ABR window and 37 dB ppe SPL for the MLR window. The 20-dB difference in threshold sensitivity between the ABR and MLR to 500-Hz tones led Picton and co-workers to conclude that the conventional ABRs to 40/s 500-Hz stimuli near threshold reported by other studies may not be true auditory brainstem responses (Picton *et al.*, 1992). Rather, they may be steady-state middle latency responses. Auditory steady-state responses are responses which are elicited by stimuli of sufficiently high rates to result in overlapping of the responses to successive stimuli (Regan, 1982; Stapells *et al.*, 1984). Picton and colleagues felt these findings may help explain some of the problems discussed above in recording 500-Hz ABRs. Indeed, several studies which have been successful in recording ABRs from the 500-Hz region of the cochlea for stimulus intensities of 55 dB ppe SPL or lower (e.g., Don *et al.*, 1979; Munnerley *et al.*, 1990; Picton *et al.*, 1979; Purdy *et al.*, 1989; Stapells *et al.*, 1995, 1990), did employ stimulus rates near 40/s, which would have enhanced the amplitude of the steady-state response (Galambos

et al., 1981; Stapells et al., 1984). Therefore, the lower thresholds reported in these studies might be a reflection of the steady-state MLR. Other investigators who had reported difficulty in obtaining 500-Hz ABRs (e.g., Laukli, 1983b; Laukli et al., 1988) employed rates of approximately 25/s, which have been shown to decrease the amplitude of the steady-state response (Galambos et al., 1981; Stapells et al., 1984). The ABR thresholds to 500-Hz tonal stimuli recorded using this lower stimulus rate would not be as sensitive due to the decrease or elimination of the steady-state response.

There are several problems with the conclusions of Picton and co-workers. First, several early ABR studies report replicable ABRs to 500-Hz tonal stimuli down to low levels (i.e., approximately 35 to 40 dB ppe SPL) in adults using stimulus presentation rates of 10-13/s (Kodera et al., 1977; Suzuki et al., 1977; Suzuki et al., 1984). Similarly, a recent study by Wu and Stapells report mean ABR thresholds of 37 dB ppe SPL for 500-Hz tonal stimuli presented at a rate of 11.9/s, compared to mean MLR thresholds of 30 dB ppe SPL (Wu and Stapells, in preparation). A second problem is that ABRs to 500-Hz tonal stimuli presented in quiet and/or notched noise have been recorded at stimulus intensities of ≤ 55 dB ppe SPL in infants and young children with normal hearing (Alberti, Hyde, Riko, Corbin, and Fitzhardinge, 1985; Hyde, 1985; Hyde et al., 1987; Suzuki et al., 1984; Stapells et al., 1994, 1995). Infants and young children do not show the enhancements in response amplitudes seen in adults when stimuli are presented at rates of 40/s (Stapells, Galambos, Costello, and Makeig, 1988; Suzuki and Kobayashi, 1984). Therefore, these infants' low ABR thresholds to 500-Hz tonal stimuli

cannot be due to the overlapping of the steady-state middle latency response on the ABR. Taken together, these studies do not support the conclusions concerning the 500-Hz ABR drawn by Picton and colleagues (Picton et al., 1992).

F2. Review of the Literature on MLRs to Tonal Stimuli

As can be seen from the above discussion, there is a considerable body of literature on the effects of stimulus parameters on recording the ABR to tonal stimuli. The existing literature on the effects of these same stimulus parameters on the MLR is much less. In addition, the findings from many of the early studies on the MLR are compromised by the use of bandpass filter settings, roll-off slopes of the filters, and stimulus rates which are inappropriate, as will be discussed in this review.

F2.A Effects of Stimulus Intensity

Several investigators have studied the effects of varying stimulus intensity on the latency and amplitude of the MLR to tonal stimuli (Beattie and Boyd, 1985; Beattie, Moretti, and Warren, 1984; McFarland, Vivion, and Goldstein, 1977; Thornton, Mendel, and Anderson, 1977; Suzuki, Hirai, and Horiuchi, 1981; Wu and Stapells, in preparation). These studies report that the absolute latency of all the MLR peaks increases with decreases in stimulus intensity. Wu and Stapells report that the latencies of waves Na, Pa, and Nb increase by approximately 5-6 ms for nonmasked 500-Hz stimuli and by 2-4 ms for nonmasked 2000-Hz tones as stimulus intensity decreases from approximately 85 to 35 dB ppe SPL (Wu and Stapells, in preparation). The largest change in latency among the MLR peaks are seen for wave Na for both stimulus frequencies.

The peak-to-peak amplitudes of all the MLR peaks (e.g., Na-Pa and Pa-Nb) decrease with decreases in stimulus intensity. The data of Wu and Stapells show that the mean amplitudes of waves Na-Pa and Pa-Nb decrease by approximately 0.5 μ V as stimulus intensity is reduced from 85 to 25 dB ppe SPL. This change in amplitude as a function of stimulus intensity is seen in the responses to the 500- and 2000-Hz tonal stimuli. The decline in amplitude is not linear, however, with the majority of the changes in amplitude occurring as stimulus intensity decreases from 55 to approximately 25 dB ppe SPL. This finding of nonlinear growth in amplitude is in agreement with Özdamar and Kraus, who report that the amplitude of wave Pa levels off at stimulus intensities of 80 dB ppe SPL and greater for click stimuli (Özdamar and Kraus, 1983). The response amplitudes of all the MLR peaks are significantly larger than ABR wave V-V' for all stimulus intensities (Wu and Stapells, in preparation).

Clearly identifiable and replicable MLR waves Na, Pa, and Nb can be recorded to 500-, 1000-, 2000- and 4000-Hz tonal stimuli in normal-hearing adults down to stimulus intensities of 40 dB ppe SPL and lower (Beattie et al., 1984; Davis et al., 1983; Suzuki et al., 1981; Wu and Stapells, in preparation). Wu and Stapells' data show MLR wave Pa mean thresholds of 30 dB ppe SPL for 500-Hz tones and 32 dB ppe SPL for 2000-Hz tonal stimuli. These mean threshold values are 2-5 dB more sensitive than the thresholds for waves Na and Nb (Wu and Stapells, in preparation).

F2.B Effects of Stimulus Frequency

The frequency of the tonal stimulus has differential effects on the latencies and amplitudes of the various MLR peaks, as shown in Figure 4 (Beattie et al., 1984; McFarland et al., 1977; Suzuki et al., 1981; Thornton et al., 1977; Wu and Stapells, in preparation). These

studies report that the latencies for all the MLR waves increase with decreasing stimulus frequency. When nonmasked tonal stimuli are presented at 85 dB ppe SPL, increases in waves Na, Pa, and Nb latencies of approximately 4 ms occur as stimulus frequency is decreased from 2000 to 500 Hz (Wu and Stapells, in preparation). This inverse relationship between latency and stimulus frequency is evident at all stimulus intensities with the greatest shifts in latency occurring at the lowest intensities. This trend is similar to that seen with ABR wave V.

The response amplitudes for waves Na-Pa and Pa-Nb are significantly larger in response to lower versus higher frequency tonal stimuli, as shown in Figure 4. Mean amplitudes for waves Na-Pa and Pa-Nb of approximately 0.75 μ V and 0.62 μ V are reported for responses to 85 dB ppe SPL nonmasked 500- and 2000-Hz stimuli respectively (Wu and Stapells, in preparation). The larger amplitudes of the MLR peaks to the lower versus higher frequency tones is evident at all stimulus intensities.

F2.C Effects of EEG Band Pass Filtering

The frequency content of the middle latency response was investigated by Suzuki and colleagues in order to determine the appropriate filter settings for recording the response (Suzuki, Kobayashi, and Hirabayashi, 1983). They conducted spectral analyses of the MLR and report that the main spectral energy of the adults' responses to clicks, presented at approximately 80 dB ppe SPL, is between 20 and 60 Hz, with a peak in the spectrum occurring at 40 Hz, and additional energy from 90 to 180 Hz.

Several individuals have studied the effects of varying the EEG band pass filter settings on the MLR (Gould, Crawford, Mendel, and Dodson, 1992; Kavanagh, Harker, and Tyler, 1984; Kileny, 1983; Kraus,

Reed, Smith, Stein, and Cartee, 1987; Kraus, Smith, and McGee, 1987; Scherg, 1982, Suzuki et al., 1983; Suzuki, Hirabayashi, and Kobayashi, 1984) as well as the effects of rolloff slopes on the response (Kraus et al., 1987; Scherg, 1982). These studies report that HP analog filtering produces significant latency and amplitude changes in the MLR. The measured latencies of waves Na, Pa and Nb become shorter as the HP filter setting is increased from 1 to 40 Hz. At a HP filter setting of 40 Hz, the amplitudes of waves Na, Pa and Nb are significantly reduced compared to lower HP settings and there is complete polarity reversal of waves Pa and Nb. The MLR completely disappears at a HP filter setting of 60 Hz. These decrements in latency and amplitude are due to phase shifting produced by the analog filtering as well as the elimination of low-frequency contributions to the response (Scherg, 1982; Suzuki et al., 1984, 1983). Zero-phase digital filtering, in contrast, leaves the ABR and MLR latencies as well as the morphology of the waveforms unaffected at HP filter settings of approximately 30 Hz and below, however, the amplitude of the response is reduced (Scherg, 1982; Suzuki et al., 1984, 1983). Kraus and colleagues examined the effects of HP filter settings on the detectability, latency, and amplitude of the MLR (Kraus et al., 1987a). They used two filter settings: (1) 3-2000 Hz with a 6 dB/octave slope and (2) 15-2000 Hz with a 12 dB/octave slope. These authors report that the largest amplitude for the MLR peaks are recorded using HP filter settings of 3 Hz. At this HP filter setting, however, there is also a decrease in detectability of the MLR due to the inclusion of low-frequency noise (Kraus et al., 1987a). Based on the trade-off between increased amplitude and decreased detectability of the response, Kraus and co-workers recommend that the MLR be recorded with a HP filter setting of 10-15 Hz (Kraus et al., 1987a). However, Gould and

colleagues demonstrated using the Fsp technique that a HP filter setting of 20 Hz rather than 10 Hz provides a more accurate assessment of the signal-to-noise ratio within the middle latency response time window (Gould et al., 1992). The Fsp technique provides an objective estimate of the signal-to-noise ratio for the evoked potential.

Several studies have shown that lowering the low-pass cutoff frequency from approximately 3000 to 100 Hz results in a general smoothing of the MLR but has very little effect on Na-Pa and Pa-Nb amplitudes (Kavanagh et al., 1984; Kileny, 1983; Scherg, 1982). Increases in the latencies of waves Na, Pa, and Nb, however, are reported for LP cutoff frequencies of 200 Hz and below and are due to phase shifting of the response produced by the analog filtering (Scherg, 1982). Digital filtering has been used to demonstrate that recording the MLR with very narrow bandpass analog filters (e.g., 30-100 Hz) produces what appears to be a wave Pa or sequence of MLR peaks when in fact there may be no MLR present (such as in children; Kileny, 1983). Simultaneous recordings of the ABR and MLR can be successfully accomplished by the use of wide bandpass (e.g., 10-1000 Hz) analog filters (Mackersie et al., 1993; Özdamar and Kraus, 1983; Scherg and Volk, 1983; Suzuki, Hirai, and Horiuchi, 1981; Wu and Stapells, 1994, in preparation), as these filter settings pass the spectral energy present in both of these responses.

Scherg demonstrated that increasing the steepness of the analog-filter slope (e.g., 48 dB/octave versus 6 dB/octave) distorts the MLR waveform and artificially produces new components in the response following wave Pa (Scherg, 1982). This occurs because at steep slopes there is an increase in the amount of oscillations in the filtered response (i.e., ringing) and an increase in the amount of phase shifting. Kraus and co-workers report that the amplitudes of the MLR

peaks are significantly larger when recorded with a 6 dB/octave slope compared to a 48 dB/octave slope (Kraus *et al.*, 1987b). Their study also reports the existence of a third-positive wave (latency 50 ms) when the MLR is recorded using a filter with a 48 dB/octave slope. This wave is not present when a filter with a 6 dB/octave slope is employed.

Overall, it is recommended that MLRs for adults be recorded with a HP filter setting of 10-20 Hz, a low-pass filter setting of at least 300 Hz and an analog filter slope of 12 dB/octave or less (Gould *et al.*, 1992; Kileny, 1983; Kraus, *et al.*, 1987a,b).

F2.D Effects of Stimulus Rate

Responses may be classified as either "transient" or "steady-state" responses. Transient responses are recorded to stimuli presented at a rate slow enough to allow the response to one stimulus to finish before the next stimulus occurs (Regan, 1982; Stapells *et al.*, 1984). Steady-state responses, in contrast, are elicited by stimuli presented at a sufficiently high rate to result in an overlapping of the responses to successive stimuli (Regan, 1982; Stapells *et al.*, 1984;).

Increasing stimulus presentation rate from 1 to 15/s has little effect on the latencies or peak-to-peak amplitudes of the transient middle latency response in adult humans (Goldstein, Rodman, and Karlovich, 1972; McFarland, Vivion, Wolf, and Goldstein, 1975). For rates of 16/s or higher, however, there is a decrease in amplitude and thus response detectability as well as an increase in response latency (McFarland *et al.*, 1975; Picton *et al.*, 1974).

When auditory stimuli are presented at a rate of greater than 30/s, a steady-state response (SSR) is recorded and there is an exception to this general trend of decreasing amplitude with increasing stimulus rate. At a stimulus rate of 40/s, a sinusoidal response similar

to a 40-Hz sinusoid is recorded from the scalp. This response has been labeled the "40-Hz auditory event related potential, or 40-Hz ERP" (Galambos et al., 1981). In normal-hearing adults, the amplitude of the MLR at rates of 40/s is approximately two to three times greater than when stimuli are presented at rates of 10/s (Galambos et al., 1981; Stapells et al., 1984; Suzuki and Kobayashi, 1984). The amplitude/rate functions of the MLR show a large peak at 40/s with a smaller peak at 20/s and the lowest amplitudes of the response at rates of 27 and 55/s (Galambos et al., 1981; Hari, Hämäläinen, and Joutsiniemi, 1989; Stapells et al., 1984, 1988). In 1981, Galambos and colleagues suggested that the enhancement in response amplitude seen at rates of 40/s is due to the superimposition of successive negative and positive peaks of the response (Galambos et al., 1981). Specifically, they hypothesized that each negative-positive cycle to a stimulus presented at a rate of 10/s lasts approximately 25 ms. When stimuli are presented at a rate of 40/s, these negative-positive cycles occur in phase and add together to produce a response with a larger amplitude. At rates of 27 and 55/s, the successive 40-Hz waves are out-of-phase and thus cancel during the averaging process. Stapells and co-workers subsequently showed that the 40-Hz SSR can indeed be created by the superimposition of the negative-positive waves present in the 10-Hz MLR (Stapells et al., 1988). These authors compared the response amplitude and phase values from actual SSRs recorded to 43.4 Hz clicks (100 dB ppe SPL) to synthesized SSRs constructing from MLRs recorded to 10.85 Hz clicks, and determined that for their adult subjects the 40-Hz SSR could be accurately predicted by superimposing the responses elicited to the 10.85 Hz clicks. Subsequent studies have shown that both the magnetic and electrical 40-Hz SSRs can be estimated reliably from superimposition of the transient MLRs

(Azzena, Conti, Santarelli, Ottaviani, Paludetti, and Maurizi, 1995; Hari *et al.*, 1989; Plourde, Stapells, and Picton, 1991; Santarelli, Maurizi, Conti, Ottaviani, Paludetti, and Pettorossi, 1995).

Using conventional averaging techniques, a stimulus rate of $\leq 15/s$ must be employed in order to see the ABR and MLR separately, without any overlapping, or any significant decreases in the amplitude of the MLR (Galambos *et al.*, 1981; McFarland *et al.*, 1975; Picton *et al.*, 1974; Stapells *et al.*, 1984).

F2.E Effects of Stimulus Rise Time

Only a few studies have investigated the effects of varying stimulus rise time and duration on the middle latency response to tonal stimuli (Beiter and Hogan, 1973; Lane, Kupperman, and Goldstein, 1971; Skinner and Antinoro, 1971; Vivion, Hirsh, Frye-Osier, and Goldstein, 1980). The studies completed in the early 1970s limited their investigations to one stimulus frequency (*i.e.*, 1000 Hz) and usually only a single intensity (approximately 65-70 dB ppe SPL). Two of these early studies did not report the filter settings or rolloff slopes employed and therefore it is difficult to evaluate their results in light of the effects of filtering on the MLR discussed above (Lane *et al.*, 1971; Skinner and Antinoro, 1971). Vivion and colleagues studied the effect of rise/fall times and stimulus duration on the MLR to tonal stimuli in greater depth (Vivion *et al.*, 1980). They elicited the MLR to 500-, 1000- and 3000-Hz tonal stimuli with rise/fall times of 3, 5, and 10 ms in combination with equivalent plateau durations of 0, 10, or 30 ms. Equivalent plateau duration is defined as two-thirds of the rise time plus the plateau duration. They used a bandpass filter of 25-175 Hz and evaluated the effects of rise/fall time and duration at stimulus intensities of approximately 35, 45, and 60 dB ppe SPL. These

investigators report that increasing the stimulus rise time from 3-10 ms results in small increases (i.e., 1-3 ms) in the peak latency for all the MLR peaks (Vivion et al., 1980). The peak latencies also increase slightly as stimulus duration is increased. This effect is essentially the same across frequencies. The finding by Vivion and co-workers of a minimal effect of rise/fall time and duration on MLR peak latencies is in agreement with earlier studies by Lane et al. and Skinner and Antinoro (Lane et al., 1971; Skinner and Antinoro, 1971; Vivion et al., 1980).

Vivion and co-workers report a significant decrease in the amplitude of the MLR peaks with increases in stimulus rise time and duration (Vivion et al., 1980). This decrease in amplitude is evident at all stimulus frequencies and is generally consistent across stimulus intensities. The greatest changes in amplitude occur when stimulus rise time are greater than 5 ms. This finding is in agreement with Beiter and Hogan, who demonstrated that response amplitudes decrease by almost 50% as rise-time is increased from 250 μ s to 25 ms, with the largest decrement occurring between 5 and 10 ms (Beiter and Hogan, 1973). From the ABR and MLR literature, it would appear that stimuli with rise times of 5 ms or less are optimal for recording the ABR and the MLR, although further research on the effects of rise time and/or stimulus duration on the MLR is needed.

F2.F Effects of Stimulus Temporal Shaping

To date, no published studies have investigated the effects on the MLR of temporal shaping of the stimuli. This may be due to the fact that many have believed that MLRs can be recorded to tonal stimuli with longer rise times. The longer-duration tones have greater acoustic frequency specificity and thus there would be less need for the

nonlinear-gated stimuli to improve the frequency specificity of the MLR. As discussed above, however, the ABR and MLR rise-time literature does not suggest a difference in the effective duration of the tonal stimuli for these two responses, and therefore the effects of temporal shaping of the stimuli on the evoked potentials is an equally important issue for the ABR and the MLR.

F2.G Effects of Masking on MLR to Tonal Stimuli

There is a paucity of research available on the use of masking to investigate the frequency specificity of transient middle latency responses. Only three published studies to date have employed masking techniques to directly investigate the frequency specificity of the transient MLRs to tonal stimuli (Mackersie *et al.*, 1993; Smith, Mills, and Schmiedt, 1990; Wu and Stapells, 1994). These three studies compared the frequency specificity of the ABR to the MLR using pure-tone masking paradigms. Smith *et al.* (1990) employed forward masking of 2000-Hz probe tones with four gerbils. This study reports that MLR frequency tuning curves have a similar "V" shape but greater width than the ABR curves, and that the MLRs are more susceptible to pure-tone masking than the ABR. Based on these findings, Smith *et al.* conclude that the MLR is less frequency specific than the ABR. Opposite conclusions were reached by Mackersie *et al.* and by Wu and Stapells, who tested 8-12 human adult subjects with a simultaneous masking paradigm (Mackersie *et al.*, 1993; Wu and Stapells, 1994). Mackersie and colleagues employed a 60 dB ppe SPL 2000-Hz probe tone, and Wu and Stapells used a 60 dB ppe SPL 500-Hz probe tone. These two studies support the conclusion that there are no differences in frequency specificity between the MLR and ABR for either probe frequency. The authors further report that there are no significant differences in the effects of pure-tone masking on the

amplitudes of the MLR and ABR. The contradictory findings between Smith et al. (1990) and these two later studies may be related to the differences in the masking technique used, differences in adaptation characteristics for the ABR and MLR, and/or differences in the human and gerbil MLR generators. To date, no one has investigated the frequency specificity of the transient MLR to moderate to high-intensity tonal stimuli, and this information is needed to determine the potential benefit of including the MLR in threshold evaluations.

G. The High-Pass Noise/Derived Response Technique

It has been suggested that the HP/DR technique yields the most frequency and place-specific evaluation of an electrophysiologic response, due to its use of HP noise masking, where no downward spread of masking occurs because of the steep high-frequency edge of the travelling wave in the cochlea (Stapells et al., 1994, 1985). It is a technique that may be used with ABRs, MLRs, or cortical responses (e.g., Burkard and Hecox, 1983; Don and Eggermont, 1978; Don et al., 1979, Eggermont, 1976; Eggermont and Don, 1980; Kramer, 1992; Noursak and Stapells, 1992; Ponton, Don, and Eggermont, 1992; Ponton, Eggermont, Coupland, and Winkelaar, 1992; Stapells and Martin, 1993).

G1. The Purposes of the HP/DR Technique

The HP/DR technique may be used in two ways: (1) as a technique to obtain frequency-specific thresholds using broad-spectrum stimuli such as clicks (e.g., Don et al., 1979), or (2) as a technique to investigate the frequency and place specificity of responses to specific stimuli, such as to clicks (e.g., Don and Eggermont, 1978; Eggermont and Don, 1980) or to 500- versus 2000-Hz tonal stimuli (e.g., Eggermont, 1976; Kramer, 1992; Noursak and Stapells, 1992).

G2. Description of HP/DR Technique

In the HP/DR technique, the ABR and/or MLR to either a click or a tone is initially recorded in quiet and then simultaneously with broadband noise of sufficient intensity to completely mask the response. The evoked potential to the stimulus is then recorded in the presence of HP noise at various cutoff frequencies. The response in HP noise at one cutoff frequency is subtracted from the response obtained in the presence of HP noise with a higher cutoff frequency. The result is a "derived response" to the frequencies between the two cutoff settings. The center frequency (CF) of the derived band will vary depending on the slope of the filter employed and the filter cutoff frequencies. Employing noise with a 96 dB/octave slope, the calculated CF of the derived one-octave-wide narrowband region is slightly above the lower of the two contributing HP noise cutoff frequencies (Don et al., 1979). The CF of the derived half-octave-wide narrowband region with the same 96 dB/octave slope to the noise is slightly below the lower of the two contributing HP noise cutoff frequencies (Don and Eggermont, 1978). In this thesis study, the HP filter will have a nominal slope of 115 dB/octave, and the CFs of the full- and half-octave- wide derived bands will be determined from the masking noise spectra (e.g., Don and Eggermont, 1978; Noursak and Stapells, 1992).

G3. Validity of the HP/DR Technique

There have been several studies which have demonstrated the validity of the HP/DR technique (Don et al., 1979; Elberling, 1974; Evans and Elberling, 1982; Parker and Thornton, 1978a,b). Parker and Thornton studied the effect of masking within the derived band by simulating a hearing loss in normal-hearing subjects with masking noise which matched the intensity and frequency characteristics of the derived

band (Parker and Thornton, 1978b). The authors hypothesized that if the electrophysiologic response was truly initiated by activity at a certain location along the cochlear partition represented by the derived band, then an individual who had a true or simulated sensorineural hearing loss at frequencies within this derived band should have a modified or absent derived response from that particular derived band. Parker and Thornton showed that narrowband masking within the DR band (i.e., simulating a hearing loss) significantly reduced the DR amplitude measures from this band while leaving the amplitude and latency measures from adjacent bands unaffected (Parker and Thornton, 1978b).

Evans and Elberling demonstrated the validity of the HP/DR technique by obtaining direct cochlear-nerve fiber recordings in cats and comparing the calculated derived response CAPs to the mapping of these individual cochlear-nerve fibers (Evans and Elberling, 1982). They found that: (1) the frequency selectivity of the individual cochlear-nerve fibers is sharp; (2) their behavior under HP masking conditions is straightforward and predictable, especially for the higher frequency fibers; and (3) the HP/DR technique does yield cochlear-fiber activity that is limited to the frequency regions between the response cutoffs. In comparing human and cat cochlear mapping and critical band studies, Evans and Elberling conclude that the HP/DR technique is valid for testing in humans for frequencies from approximately 500 through 16,000 Hz (Evans and Elberling, 1982).

The validity of the HP/DR technique has also been supported by successful evaluation of individuals with cochlear hearing loss. Studies by Elberling and by Don et al. have shown that the HP/DR technique can yield reasonably accurate reconstruction of the pure-tone audiogram in subjects with low-frequency, high-frequency or flat hearing loss and hearing losses that are restricted to just one frequency (Elberling,

1974; Don et al., 1979). A study by Stapells, however, showed that the HP/DR technique is not as sensitive a tool for estimating thresholds in the low frequencies and significantly overestimated the degree of hearing loss at 500 Hz (Stapells, 1984).

G4. Advantages of the HP/DR technique Compared to Other Masking Techniques For Investigating the Frequency Specificity of Evoked Potentials

The primary advantage of the HP/DR technique over either the ABR to nonmasked tones or the response to tones in notched noise is that there is little or no upward spread of masking because the HP/DR technique utilizes only HP noise in comparison to the HP and low-pass (LP) noise employed in the notched-noise technique. Therefore, the HP/DR technique yields the most frequency- and place-specific evaluation of the response (Stapells et al., 1994; 1985).

G5. Disadvantages of the HP/DR Technique in Comparison to Pure-Tone and/or Notched Noise Masking in Determining the Frequency Specificity of the Response

The primary disadvantage of the HP/DR technique is that the subtraction procedure decreases the signal-to-noise ratio of the response. The subtraction of the response increases the root-mean-square (RMS) value of the noise by a factor of 1.4 (i.e., $\sqrt{2}$). To counteract this effect, one must average twice as many trials (e.g., 8000 versus 4000 sweeps). Another disadvantage is that this technique limits the maximum intensity of the stimulus that may be safely employed to

approximately 70-80 dB ppe SPL, due to the high acoustic intensities of broadband noise required to completely mask the response to the tones or clicks (Stapells et al., 1994; 1985).

G6. Results from HP/DR Studies

Don and Eggermont investigated the cochlear contributions to the click-evoked ABR with the use of HP/DR technique (Don and Eggermont, 1978; Eggermont and Don, 1980). They demonstrated that when clicks are presented at approximately 90 dB ppe SPL, nearly the entire cochlear partition contributes to the auditory brainstem response. Wave I receives cochlear contributions from frequency regions of approximately 1800 Hz and above, and frequency regions of 1000 Hz and higher contribute to wave III. In contrast, cochlear contributions to wave V could be detected from as low as 425 Hz up to at least 8000 Hz. The cochlear contributions to the response change as a function of the intensity of the click. At low stimulus intensities (45-55 dB ppe SPL), only the 500-4000 Hz regions contribute to the click-evoked ABR.

The HP/DR technique has been used to investigate the frequency specificity of the ABR to bone-conducted 500- and 2000-Hz tonal stimuli (Kramer, 1992; Noursak and Stapells, 1992). The study by Kramer also determined the cochlear contributions to the ABR to bone-conducted click stimuli. The results of these two studies demonstrate that auditory brainstem responses to bone-conducted tonal stimuli are frequency specific, especially for low stimulus intensities (i.e., 16-40 dB nHL). Figure 5, adapted from Kramer's data, shows the results of utilizing the HP/DR technique to investigate cochlear contributions to ABRs to tonal versus click stimuli. The peak in the derived response amplitude profiles for ABRs to 40 dB nHL bone-conducted 500- and 2000-Hz tones occurs at each of the nominal stimulus frequencies. There are cochlear

contributions to the response to the 2000-Hz tone from regions one octave above and below the nominal stimulus frequency. The ABR to the click stimulus, in contrast, receives cochlear contributions from a broad range of frequencies (i.e., 500 to 6000 Hz).

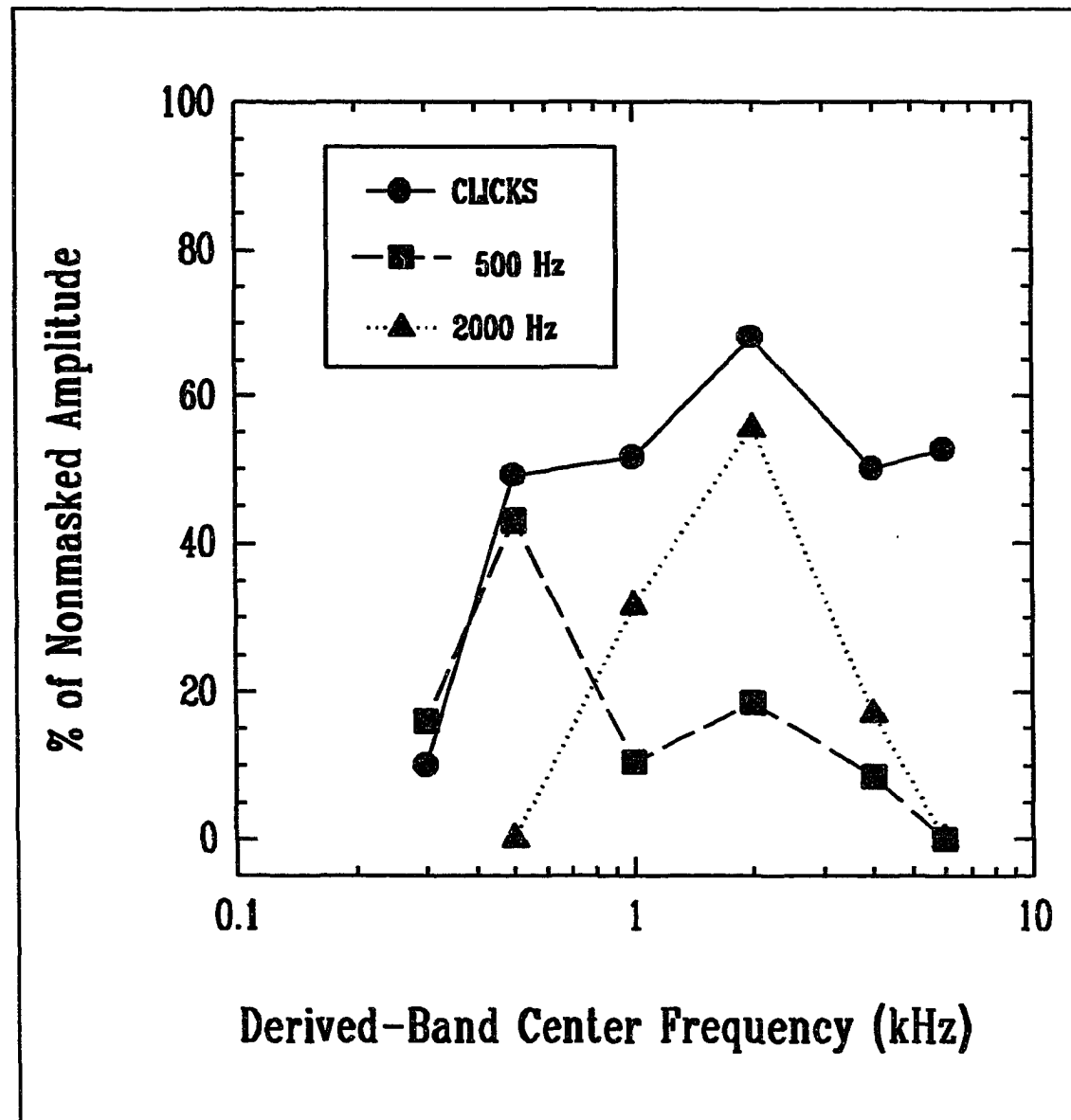


Figure 5. Derived response amplitude profiles for ABR wave V to bone-conducted click and tonal stimuli presented at 40 dB nHL. (Adapted from: Kramer, 1992).

To date, no published studies have employed the HP/DR technique to evaluate the cochlear contributions to the ABR to moderate intensity 500- or 2000-Hz air-conducted tones. This type of information is needed to better define the role of moderate to high intensity brief tones in the assessment of peripheral hearing sensitivity.

SECTION II

RATIONALE UNDERLYING THE THESIS STUDY AND SELECTION OF SPECIFIC PARAMETERS

A. Rationale Underlying the Thesis Study

An important clinical application of electrophysiologic testing is the assessment of peripheral hearing sensitivity in children and/or adults who cannot be tested reliably with conventional behavioral audiometric techniques. Two electrophysiologic measures that have been recommended for threshold evaluations are the ABR and MLR. A question that has been raised in terms of their clinical application has been "How frequency and place specific are these responses?"

A reasonably efficient method to obtain a frequency-specific evoked potential is to use a frequency-specific stimulus (i.e., a brief tone) rather than a broad-band stimulus (i.e., a click). There have been several areas of controversy, however, with regard to the clinical utility of ABR and MLR to tonal stimuli. Some studies have suggested that: (1) the ABR to high-intensity (≥ 80 dB ppe SPL) 500-Hz stimuli is primarily generated from the basal end of the cochlea; (2) waveform identification of the ABR to 500-Hz stimuli is problematic in quiet, and even more so in the presence of HP masking noise; and (3) ABR thresholds to 500-Hz tonal stimuli have poor frequency specificity and thus are poor predictors of low-frequency behavioral thresholds (e.g., Davis and Hirsh, 1976; Laukli, 1983b; Laukli et al., 1988; Laukli and Mair, 1986; Scherg and Volk, 1983; Sohmer and Kinarti, 1984; Weber, 1987). In view of these controversies, a study is needed which assesses the cochlear contributions of high-intensity 500- and/or 2000-Hz air-conducted tonal stimuli to the ABR. This information is clearly needed to better define the frequency and place specificity of these responses and thus their role in threshold evaluations.

In view of the controversies regarding the use of the ABR to estimate low-frequency hearing sensitivity, the MLR has been proposed as a better indicator of 500-Hz sensitivity (e.g., Kavanagh et al., 1984;

Kileny and Shea, 1986; Palaskas, Wilson, and Dobie, 1989; Scherg and Volk, 1983; Weber, 1987). The suggestion that the MLR may be a more appropriate measure of low-frequency hearing has been based upon the observation that larger peak-to-peak amplitudes are measured for MLR waves Na and Pa in comparison to ABR wave V in response to 500-Hz tones, thus leading to better detectability of the MLR (Scherg and Volk, 1983; Wu and Stapells, 1994; Wu and Stapells, in preparation). A commonly held belief is that the MLR can be recorded using tones with longer rise times than the ABR without causing a significant decrease in the amplitude of the response. Tones with longer rise times have greater acoustic frequency specificity (Burkard, 1984; Gorga and Thornton, 1989; Jacobson, 1983; Stapells and Picton, 1981). However, the current literature on the effects of rise time on the MLR (Beiter and Hogan, 1973; Vivion et al., 1980) does not support this belief, and thus shorter rise times must be used.

Several studies have looked at various aspects of the MLR, including the effects of stimulus intensity and stimulus frequency on waves Na, Pa and Nb (e.g., Mackersie et al., 1993; Scherg and Volk, 1983; Skinner and Antinoro, 1970; Weber, 1987; Wu and Stapells, 1994; Wu and Stapells, in preparation). Only the studies by Mackersie et al. and Wu and Stapells, however, have directly investigated the frequency specificity of the MLR to tonal stimuli in humans (Mackersie et al., 1993; Wu and Stapells, 1994). These two studies have established that the MLR is a reasonably frequency-specific measure for low-intensity (i.e., 60 dB ppe SPL) 500- and 2000-Hz tones. No published research, however, has addressed the question of how frequency specific the MLR is to higher intensity 500- and 2000-Hz tones. This type of information is necessary to determine the potential clinical benefit of the MLR, especially in evaluating threshold sensitivity.

Another area of debate with respect to tonal stimuli has been the suggestion to use a nonlinear-gated stimulus (e.g., exact-Blackman window; Nuttall, 1981) in place of the more conventional linear-gated stimulus to improve the frequency specificity of the ABR (Dolan and Klein, 1987; Gorga et al., 1992; Gorga and Thornton, 1989; Telian and Kileny, 1989). Brief tones gated using the exact-Blackman window theoretically may yield frequency spectra that are more narrow than those of linear-gated tones, while still maintaining the rapid onset needed for eliciting the tones. It has been proposed that the reduction of energy in the sidelobes of the Blackman-gated tone may have the advantage of removing contributions to the evoked potential from frequencies other than the nominal frequency and thus yield a more frequency-specific response than would have been obtained with the linear-gated tone (Gorga and Thornton, 1989). This may not be the case, however, as evoked potentials to the exact-Blackman-gated tone may show poorer frequency specificity than the responses to the linear-gated tones because there may be contributions to the response from frequencies represented in the wider main lobe of the exact-Blackman tone. To date, no published studies in humans have investigated how the frequency-spectrum differences between the exact-Blackman- and linear-gated tones are reflected by the ABR and/or MLR.

As discussed in Section I, the HP/DR technique may be used to investigate the frequency specificity of evoked potentials to various stimuli, such as high- and low-frequency brief tones (e.g., Eggermont, 1976; Kramer, 1992; Noursak and Stapells, 1992). In this thesis, the HP/DR technique will be used to assess: (1) the frequency specificity and cochlear contributions to the ABR and MLR to moderate intensity (80 dB ppe SPL) 500- and 2000-Hz tones; (2) the differences, if any, in the

frequency specificity of the ABR (wave V) versus MLR (wave Na-Pa); and (3) the differences, if any, in the frequency specificity of these electrophysiologic responses to exact-Blackman- versus linear-gated tones.

B. Description of Stimulus and Masking Parameters Employed in the Thesis Study

B1. Stimuli

500- and 2000-Hz short-duration tones were presented in two conditions: (1) 2-1-2 tones, consisting of a linear rise time of 2 cycles, plateau time of 1 cycle, and linear fall time of 2 cycles; and (2) exact-Blackman tones, with a 5-cycle total duration, and no plateau. The 2-1-2 cycle tone is an approximation of the "logon" signal described by Gabor (1947) as being the best compromise between time and frequency. The relatively short rise times (2 to 2.5 cycles) for the stimuli were selected because the amplitude of both ABR wave V-V' and MLR wave Na-Pa decrease significantly when rise times of greater than 5 ms are used (Beiter and Hogan, 1973; Koderer et al., 1977; Stapells and Picton, 1981; Vivion et al., 1980).

B2. Stimulus Presentation Rate and Polarity

The 500- and 2000-Hz stimuli were presented monaurally at a rate of 9.4/second. Faster rates could not be used because the peak-to-peak amplitudes of MLR waves decrease significantly as stimulus rate increases (16/second or greater) (McFarland et al., 1975; Picton et al., 1974). This relatively slow stimulus rate was also chosen to avoid superimposition of the ABR and MLR (Galambos et al., 1981; Stapells et

al., 1984; Suzuki et al., 1984). Alternating polarity stimuli were employed in this study as the stimulus-related electrical artifacts and the cochlear microphonic (CM) occur especially at moderate to high stimulus intensities and are effectively cancelled-out by the alternation (e.g., Davis, 1976). The use of alternate onset polarity stimuli also cancelled out the frequency-following response which may occur in ABRs to 500-Hz stimuli presented at stimulus intensities of approximately 65 dB ppe SPL and above (Davis and Hirsh, 1976; Gergen, Moushegian, Stillman, and Rupert, 1975). No published studies to date have determined whether thresholds to tonal stimuli differ for rarefaction, condensation or alternating polarity stimuli.

B3. Stimulus Intensity

The exact-Blackman- and linear-gated tones were presented at equal peak-to-peak equivalent (ppe) sound pressure levels. An "equal dB SPL" approach was decided upon over an "equal dB nHL" approach in order to have a known and equal physical reference for the intensity of the stimuli. The normal hearing level (nHL) reference refers to the stimulus intensity in decibels relative to the average threshold for a particular stimulus in a group of normal-hearing adults (Picton, Woods, Baribeau-Braun, and Healey, 1977). This reference hearing threshold level depends on the repetition rate of the short-duration signals and is specific to the type of transducer employed (International Electrotechnical Commission, 1994). The disadvantage of an equal nHL approach is that there might be slightly different thresholds (in SPL) for the two stimuli. These different thresholds could be due to the subjects' differing attention during the behavioral task and/or different ambient

noise levels. Any re-calibration of the stimuli (e.g., change in earphone transducer) would require a re-evaluation of at least 10 subjects with normal hearing for each of the stimuli (Stapells et al., 1982).

The stimuli were presented at 80 dB ppe SPL. Behavioral threshold data obtained from a pilot study (see Table 1) show that the 80 ppe SPL value corresponds to levels of 53 dB nHL for the 500-Hz stimuli and 52 dB nHL for the 2000-Hz stimuli. These nHL values are similar to those of a previous study (Stapells et al., 1990). In the present study, the stimuli were thus presented at equal dB ppe SPL and essentially equal nHLs.

Table 1. Mean behavioral thresholds (dB ppe SPL) of subjects (N=10) to 500- and 2000-Hz exact-Blackman- and linear-gated tonal stimuli.

	<u>500 Hz</u>		<u>2000 Hz</u>	
	Linear	exact-Blackman	Linear	exact-Blackman
Mean	28	27	28	29
Median	25	25	26	26
SD	9	9	6	6
Range	18-44	19-44	23-41	23-42
All thresholds measurements were made with the ER3A insert earphones Stimulus Rate: 9.4/s				

The choice of 80 dB ppe SPL was based on three considerations. The initial consideration was the desire to have a high enough stimulus level to cause a spread of excitation along the basilar membrane. VIIIth nerve tuning curves indicate that there is increased spread of cochlear excitation at stimulus intensities of 80 dB SPL and greater (e.g., Rose et al., 1971). Several masking studies have demonstrated that when stimulus intensities of 80 dB ppe SPL or greater are employed, some decrement in ABR frequency tuning occurs (e.g., Burkard and Hecox, 1983; Klein, 1983; Picton et al., 1979; Stapells and Picton, 1981). These changes in frequency tuning may be reflected in the amplitudes and/or latencies of the ABR and MLR to the exact-Blackman- versus linear-gated tones.

The second consideration was the need to avoid potentially harmful levels of masking for the HP noise conditions. From pilot studies, it was determined that noise of too high an intensity was required to mask 85 dB ppe SPL tones, whereas that required for 80 dB ppe SPL tones was within reasonable safety margins and acceptable subject comfort levels. The "minimum effective time" below which no significant temporary or permanent threshold shift should occur was estimated by the formula: $1.06 r(S-85) (\log_{10} T/1.7)$ (Ward, Glorig, and Sklar, 1958). According to formula, "r" = the duty cycle of the noise, "S" = the SPL of the noise, and "T" = the total duration of exposure (in minutes). The term "duty cycle" of the noise refers to the percent of total time the masking noise is on. This formula predicts that the intensity of broadband noise required to mask 80 dB ppe SPL 500- or 2000-Hz tones would produce a maximum TTS of 5 dB or less after at least 15 minutes of exposure when employing a 100% duty cycle. A TTS of 5 dB or less is not considered a significant change in hearing sensitivity. The calculations are displayed in Table 2.

Table 2. Prediction of Maximum Temporary Threshold Shift (TTS) for 80 dB ppe SPL 500- and 2000-Hz tones.

Stimulus	Maximum Required BBN (dBSPL) (S)	Duty Cycle of noise (%) (r)	Expected Duration of Exposure (min) (T)	Predicted TTS (dB)
500 Hz	90	100	15.6 ^a	5.1
2000 Hz	88	100	15.6 ^a	3.06
Note. $TTS (dB) = 1.06r(S-85) \times (\log_{10} T/1.7)$ according to Ward, Glorig, and Sklar (1958) formula. Expected total duration estimates allow for 10% stimulus artifact rejection. ^aExpected duration of exposure = Maximum of 8800 trials at 9.4/s = 15.6 minutes.				

The third consideration in selecting 80 dB ppe SPL was the desire to minimize nonlinearities in the auditory system which are greater at higher stimulus intensities (Tonndorf, 1973; Robles and Rhode, 1974).

B4. Earphone Transducers

The tonal stimuli and broadband noise were presented to the subject using Etymotic Research ER-2 insert earphones. Insert earphones

were selected over conventional earphones (e.g., TDH-49) in order to maximize the subject's comfort during the test sessions. ER-2 insert receivers were chosen instead of the ER-3A transducers because of their broader frequency response (i.e., 100 to 16,000 Hz for the ER-2 and 100-8000 Hz for the ER-3A). If there were cochlear contributions to the responses to 80 dB ppe SPL 2000-Hz stimuli from frequencies above 8000 Hz they would have been attenuated by the ER-3A earphones. The ER-2 insert earphone tested in a Zwislocki coupler has a flat frequency response from less than 100 Hz to approximately 16,000 Hz. The frequency response measured in a 2-cc coupler (Brüel and Kjaer model DB0138, as recommended by Etymotic Research) is essentially flat through 1000 Hz and has a rolloff slope of at least 3 dB/octave above this frequency. The calibrations took into account correction factors for the 2-cc coupler to the Zwislocki coupler, and corrected the SPL to reach 80 dB ppe SPL for both the 500- and 2000-Hz stimuli.

B5. Intensity of Broadband Noise Masking

The intensity of broadband "pink" noise required to mask the ABR and MLR to 80 dB ppe SPL exact-Blackman- and linear-gated 500- and 2000-Hz tones was determined behaviorally from a pilot study conducted on 10 normal-hearing adults. The pilot data are in agreement with similar data reported by Purdy et al. (1989). For this thesis study, the maximum masker intensity measured from the pilot study was increased in 1-dB steps until the ABR and MLR were judged to be completely masked by the examiner for each subject. The mean masker intensity employed in the thesis study was 92 dB SPL (range = 90-93 dB SPL).

B6. HP Noise Cutoff Frequencies and Derived Bands

The tonal stimuli were presented in quiet or simultaneously with broadband "pink" noise or HP filtered noise (115 dB/octave slope). Pink noise was selected over white noise as it has been demonstrated that when white noise is presented at a fixed intensity, there is a greater masking effect (i.e., greater threshold shifts) seen for the high versus low frequencies (Hawkins and Stevens, 1950). Pink noise has a rolloff of approximately 3 dB/octave towards the higher frequencies, and therefore counterbalances the greater masking effects that occur in the high-frequency regions. Most HP/DR studies have used pink noise (e.g., Don and Eggermont, 1978; Don, Ponton, Eggermont, and Masuda, 1993; Eggermont and Don, 1980; Ponton et al., 1992). The HP noise cutoff frequencies for the 500- and 2000-Hz stimuli are displayed in Table 3. Half-octave HP masking conditions were included in this study because it may be that at least half-octave steps are required to detect a difference in response amplitudes and/or latency shifts between the linear and nonlinear envelopes. Noursak and Stapells (1992) demonstrated that the maximum derived-response amplitude to 70 dB (re:1 dyne RMS) 2000-Hz bone-conducted tones for infants was obtained within a half octave of the nominal frequency (1410-2000 Hz). Smaller steps (e.g., 1/3 or 1/4 octave steps) were not included in this study due to the amount of time required for data collection and the fact that differences revealed by small frequency separations probably have little practical significance. The electrical spectra of the broadband pink noise and the various HP noise conditions employed in this study can be seen in Figure 6a.

Estimates of the derived bands were obtained by subtracting, in succession, the electrical spectrum of the HP noise at one cutoff frequency from the spectrum of the HP noise at the next higher cutoff frequency (Don and Eggermont, 1978; Noursak and Stapells, 1992). This

technique was applied to determine both the one-octave-wide and half-octave-wide derived bands. Figures 6b and 6c represent estimates of the full and half-octave derived bands, respectively. The center frequencies of these full and half-octave derived bands are shown in Table 3.

The nominal derived bands for the full and half-octave analyses can be seen in panels b and c of Figure 6, and are shown in Table 3. The actual center frequency of the narrowband regions contributing to the full and half-octave responses was measured from the acoustic-noise spectra. The calculated center frequencies for the derived bands for the full and half-octave analyses are displayed at the bottom of Table 3, and are close to the "nominal center frequencies".

C. Description of Recording Parameters Employed in Thesis Study

C1. EEG Band Pass Filters and Rolloff Slope

Electroencephalographic (EEG) signals were amplified (gain = 100,000) and analog filtered using a bandpass of 10-3000 Hz and a rolloff slope of 6 dB/octave. The choices of appropriate EEG amplifier HP filter settings for recording these electrophysiologic responses were limited by the equipment (GRASS model 12) to either 10 or 30 Hz. A HP filter setting of 10 Hz was selected because the MLR is significantly attenuated by HP filter settings above 20 Hz (Gould et al., 1992; Kileny, 1983; Kraus et al., 1987a; Suzuki et al., 1984). Secondly, the use of analog HP filter settings above 10 Hz causes phase distortion of the MLR (Scherg, 1982; Suzuki et al., 1984). The ABR to 500-Hz tones is also particularly sensitive to low HP filter settings because the dominant electrical frequencies of the ABR to 500-Hz tones are significantly lower than those for the higher frequency stimuli (Suzuki and Horiuchi, 1977; Stapells and Picton, 1981). Both of these

Table 3. Nominal and Calculated Derived-Band Center Frequencies (kHz)

500-Hz TONESFull-Octave Derived-Band Center FrequenciesNominal 2.0, 1.410, 1.0, 0.707, 0.50, 0.354, 0.25Calculated 2.2, 1.525, 1.1, 0.775, 0.55, 0.425, 0.25Half-Octave Derived-Band Center FrequenciesNominal 2.83, 2.00, 1.41, 1.00, 0.707, 0.50, 0.354, 0.25Calculated 2.675, 1.875, 1.325, 0.925, 0.65, 0.45, 0.325, 0.225**2000-Hz TONES**Full-Octave Derived-Band Center FrequenciesNominal 4.00, 2.83, 2.00, 1.41, 1.00, 0.707, 0.50Calculated 4.575, 3.10, 2.20, 1.525, 1.10, 0.775, 0.55Half-Octave Derived-Band Center FrequenciesNominal 5.66, 4.00, 2.83, 2.00, 1.41, 1.00, 0.707, 0.50Calculated 5.40, 3.68, 2.68, 1.88, 1.33, 0.93, 0.650, 0.45

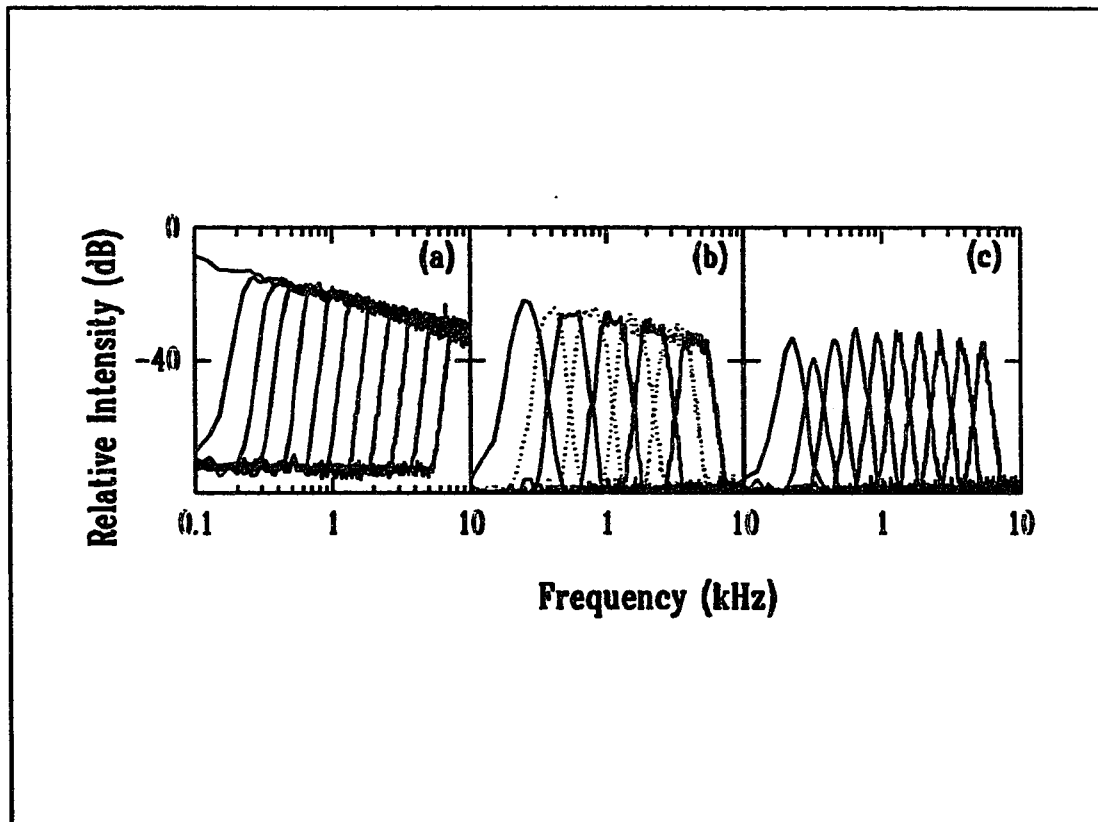


Figure 1. (a) Electrical spectra of pink noise and HP noise, (b) one-octave-wide derived bands obtained by subtraction of HP noise maskers separated by full octaves, (c) derived bands obtained by subtraction of HP noise maskers separated by half octaves.

electrophysiologic responses are affected by steep-rolloff slopes (Hyde, 1985; Kileny, 1983; Kraus et al., 1987b; Scherg, 1982; Stapells and Picton, 1981). The analog filter settings and rolloff slopes selected permit simultaneous recordings of the subjects' ABRs and MLRs. The evoked potentials were *post hoc* digitally filtered employing a band pass filter of 20-1000 Hz. The digital filtering was carried out using the Neuroscan "SCAN" system which simulates a Butterworth filter with a zero phase lag. Digital filtering at a LP setting of 1000 Hz (96 dB/octave slope) removed the high-frequency electrical noise present in the

recording without affecting the ABR or MLR. Suzuki and colleagues have shown that the use of a 20-Hz HP (24 dB/octave slope in the present study) filter setting decreases response variability for both adults and children (Suzuki et al., 1984). The advantage of zero-phase digital filtering is that it does not introduce any phase distortion which would have been produced by narrow analog filtering. In the present study, waveforms were filtered in the frequency domain using forward and inverse FFTs. The data were not windowed prior to these FFTs.

C2. Electrode Montage

EEG signals were monitored using gold-plated electrodes placed on the vertex (Cz) and earlobe (A1 or A2) of each subject, with the forehead electrode (Fpz) serving as ground. The earlobe location was utilized for the inverting electrode to minimize the postauricular muscle reflex which could distort the later waves of the ABR (Picton et al., 1974; Stapells and Picton, 1981) and/or the early waves of the MLR (Bickford, Jacobson, and Cody, 1964; Picton et al., 1974; Harker, Hosick, Voots, and Mendel, 1977). This electrode montage permitted ipsilateral recordings of the subject's ABRs and MLRs. Monitoring of the EEG activity alerted the examiner to any changes in the patient's relaxation state as well as potential electrode problems. Interelectrode impedances were 2000 Ohms or less.

C3. Digitization Parameters

The EEG signals were digitized (12-bit converter) using a sampling rate of 12,128 Hz. Sweeps consisted of 1024 points over an 84-ms window, including a 3-ms pre-stimulus baseline.

C4. Number of Response Replications and Trials

Eight replications of 1000 trials each (for a total of 8000 trials) were obtained in the quiet, broadband noise, and various HP-noise conditions. A total of 8000 trials was decided on in order to improve the signal-to-noise ratio. Subtraction of the responses required for the derived response technique increases the RMS value of the noise by a factor of 1.4 ($\sqrt{2}$). Pilot data on the derived responses employing 4000 trials were quite noisy and therefore increasing the total number of trials to 8000 counteracted the additional noise produced by the subtraction procedure. A decision was made to collect the data in blocks of 1000 sweeps in order to maximize patient comfort and to limit extraneous muscle movement during recordings.

C5. Derived Responses

The derived responses were obtained by subtracting, in succession, individual recordings of the electrophysiologic responses to the tones in HP noise at one cutoff frequency from the responses to the same frequency tones with a higher-cutoff frequency. The HP/DR subtraction procedure resulted in seven separate DRs for full-octave analyses and eight DRs for the half-octave analyses. For clarity of presentation in this thesis study, the center frequency of the derived responses will be labeled as the frequency of the lower of the two HP cutoff-frequency settings present in the subtraction process (Don *et al.*, 1979; see Table 3).

C6. Response Identification

The use of objective signal-to-noise ratios (SNR) in place of subjective ratings of the response has been advocated to improve the accuracy of identifying replicable evoked potentials (e.g., Don,

Elberling, and Waring, 1984; Elberling and Don, 1984; Picton, Linden, Hamel, and Maru, 1983; Schimmel, 1967; Schimmel, Rapin, and Cohen, 1974; Valdes-Sosa, Bobes, Pérez-Abalo, Perera, Carballo, and Valdes-Sosa, 1987; Wong and Bickford, 1980). Three statistical indexes that appear best suited to providing objective estimates of SNRs of transient evoked potentials are: (1) Standard Deviation Ratio (SDR), (2) Fsp, and (3) Hotelling's T²R.

At present, however, two major problems arise in applying any of these statistical measures. First, the Neuroscan equipment does not allow for the subtraction of single trial data which is required for Fsp analysis of the derived responses. Secondly, no published literature exists on the use these statistical measures with ABRs and MLRs, or for responses to tonal stimuli. Given the differing morphologies, amplitudes and latencies of the ABR and MLR to 500- and 2000-Hz tonal stimuli, inclusion of an objective SNR measure would require a major study in itself.

In view of the equipment difficulties as well as the lack of published research available on these objective measures, a decision was made that rating of the responses by human observers according to pre-determined criteria would be more appropriate than the objective SNR techniques which are, as yet, not well investigated.

The decisions regarding the presence or absence of the ABR and MLR were made by three individuals who are familiar with auditory evoked potentials, their measurements, and the ABRs and MLRs recorded and printed by the Neuroscan equipment. A decision to use only experienced raters was made because Valdes-Sosa et al. (1987) reported that there was greater stability in the discrimination ratings of their experienced versus inexperienced judges.

Each subject's ABR/MLR waveforms were combined into waveform sets. A set of ABR/MLR waveforms included the overall average (8000 trials), two replications of 4000 trials each, and four replications of 2000 trials each. Each set was plotted out on a -3 to 81 ms time window for each stimulus in the quiet, broadband noise, nine HP noise conditions, and 15 derived response conditions (seven full-octave and eight half-octave) resulting in 104 sets of waveforms per subject. Each judge was given a printout of a set of ABR and MLR waveforms for the nonmasked as well as for each of the HP noise and derived response conditions. All three judges had knowledge of the frequency of the stimulus, however, they were blind to the type of stimulus (exact-Blackman versus linear), the HP noise cutoff frequency, and the center frequency of the derived response. The order of rating the various HP noise and derived response conditions, as well as the order of the subjects, were randomized for each rater. Each rater scored the ABR and MLR waveforms independently of the other raters.

The raters were given the following as guidelines for response presence: (1) the peaks of the responses must occur within the appropriate time windows (i.e., ABR wave V: 6 - 20 ms; MLR wave Pa: 20 - 50 ms); (2) the difference between the absolute latencies of waves V and Pa in the replicate tracings contributing to the grand average could not exceed one-half of the standard deviation of these measurements in the normal population (Picton and Maru, 1984); and (3) considering the 10-ms period surrounding the wave V and wave Pa peaks, the peak-to-peak amplitude of the grand average must be at least 3X the average distance between the replicate tracings contributing to the average (Picton and Maru, 1984). These latency and amplitude criteria must be met in either 3/4 of the 4 x 2000 trial plots, or in 2/2 of the 2 x 4000 trial plots. The Wu and Stapells (1995) data for 10 subjects with normal hearing show

standard deviations for wave V latency (65 dB nHL 500- and 2000-Hz tones) of 1.6 ms and 1.0 ms, respectively, and standard deviations for wave Pa latency of 3.1 ms and 2.7 ms, respectively.

C7. Response Criteria

Each of the raters independently assigned a score of "1" to "4" to ABR wave V and MLR wave Pa in the grand average for the various HP noise and derived response conditions. These waves were scored based on visual observation of the 10-ms window centered on the peak latency of the response. The raters assigned a score of "4" if the amplitude of the response was at least 3X the average difference between the replicate tracings contributing to the grand average in 3/4 of the 4 x 2000-sweep plots and in 2/2 of the 2 x 4000-sweep plots. A score of "3" was assigned when the amplitude of the response was 3X the average difference between the replicate tracings in either 3/4 of the 4 x 2000-sweep plots or in 2/2 of the 2 x 4000-sweep plots. A score of "2" was given when the amplitude was approximately 1 - 1.5X the average difference between the replicate tracings in either the 4 x 2000-sweep plots or the 2 x 4000-sweep plots, but did not satisfy the 3/4 or 2/2 conditions. Lastly, a score of "1" was used when there was no replicable response in either of the plots contributing to the grand average and the tracings clearly indicated residual noise. The significance of the scores was as follows: a score of "4" indicated a definite response; "3" a probable response; "2" probably no response; and "1" definitely no response. The raters were instructed to rate each peak separately and therefore might have assigned different scores for specific peaks in the response. The three raters' scores were averaged and this average was then rounded off to the nearest integer for each of the waveform peaks.

Waveform peaks with a mean score (across the three raters) of "3-4" were judged as responses, and those with a mean score of "1-2" indicated no response (Stapells, 1984; Stapells et al., 1990).

Actual response criteria employed by experienced judges are multidimensional and not as simple as outlined above. Therefore, in order to ensure agreement between the three judges, interjudge agreement was assessed in a pilot study of a large set (i.e., 180) of ABR/MLR waveforms to 500- and 2000-Hz tonal stimuli. This set did not include any of the waveforms in the current study. These pilot waveforms contained responses that were representative of all four rating categories. In the thesis study, the three judges showed high interjudge reliability, with Gamma probabilities ranging from .844 to .922.

SECTION III

COCHLEAR CONTRIBUTIONS TO THE HUMAN AUDITORY BRAINSTEM AND MIDDLE LATENCY RESPONSES TO BRIEF TONES

**COCHLEAR CONTRIBUTIONS TO THE HUMAN AUDITORY BRAINSTEM AND
MIDDLE LATENCY RESPONSES TO BRIEF TONES***

Peggy A. Oates^{1,2} and David R. Stapells^{1,2,3}

Doctoral Program in Speech and Hearing Sciences²

C.U.N.Y. Graduate Center, New York, N.Y.

and

Department of Otolaryngology¹ and Neuroscience³

Albert Einstein College of Medicine, Bronx, N.Y.

Running Head: Frequency Specificity of ABR and MLR

* Presented at the 18th midwinter research meeting of the Association for Research in Otolaryngology, St. Petersburg, FL, February 7, 1995; and at the Fourteenth Biennial Symposium of the International Electric Response Audiometry Study Group, Lyon, France, August 29, 1995

ABSTRACT

This study investigated the frequency specificity of the auditory brainstem (ABR) and middle latency (MLR) responses to 500- and 2000-Hz brief tones using the high-pass noise masking/derived response technique. Stimuli were linear- (2-1-2 cycles) and exact-Blackman- (5 cycles) gated tones presented at 80 dB peak-to-peak equivalent (ppe) SPL. Cochlear contributions to ABR wave V-V' and MLR wave Na-Pa were assessed by: (1) effects of high-pass noise masking on response amplitudes and latencies; and (2) response amplitude profiles as a function of derived-band center frequency. Results for 1-octave- and $\frac{1}{2}$ -octave-wide derived bands were obtained for 12 normal-hearing adults.

The high-pass noise and derived response results demonstrate that the ABR and the MLR to 80 dB ppe SPL brief tones show good frequency specificity. Changes in ABR or MLR amplitude and latency with high-pass noise masking did not occur until the masker cutoff was within one-half octave of the stimulus nominal frequency. The largest amplitudes of ABR wave V and MLR wave Na-Pa occurred in the 500- and 707-Hz derived bands for the exact-Blackman- and linear-gated 500-Hz tones. The peak in the response amplitude profiles for ABR wave V to both 2000-Hz stimuli was seen in the 2000-Hz derived band. For MLR wave Na-Pa, the maxima in the amplitude profiles occurred in the 2000- and 1410-Hz derived bands for the exact-Blackman- and linear-gated tones. Cochlear contributions to the ABR and MLR to these tones were also present but smaller at 0.5 to 1 octave above and below the nominal frequencies of the stimuli.

In conclusion, the ABR/MLR to 500- and 2000-Hz 80 dB ppeSPL tones show good frequency specificity, with no significant differences in the frequency specificity of: (1) ABR versus MLR; (2) these evoked potentials to 500- versus 2000-Hz tones; and (3) responses to exact-Blackman- versus linear-gated tones.

INTRODUCTION

The Auditory Brainstem Response (ABR) and Middle Latency (MLR) Responses to brief tones consist of a series of positive and negative waves which occur within the first 75 ms following stimulus onset. Both the ABR and MLR have been suggested for use in estimating pure-tone behavioral thresholds, thus highlighting the importance of defining the frequency and place specificity of these responses. The frequency specificity of an audiometric measure is a term generally applied to threshold evaluations and refers to how independent a threshold at one stimulus frequency is of contributions from surrounding frequencies (Stapells, Picton, and Durieux-Smith, 1994; Stapells, Picton, Pérez-Abalo, Read, and Smith, 1985). Cochlear place specificity, in contrast, refers to the portion of the basilar membrane contributing to the response. Three areas of controversy with respect to the frequency and place specificity of these evoked potentials to tonal stimuli are: (1) the use of low-frequency stimuli (i.e., 500 Hz) at high stimulus intensities for recording the ABR; (2) the suggestion that the MLR provides a more frequency-specific response to low-frequency tones compared to the ABR; and (3) the use of nonlinear-gated stimuli (e.g., Blackman-gated tone) versus conventional linear-gated tones to improve the frequency specificity of the ABR and/or MLR.

A reasonably efficient method to obtain a frequency-specific evoked potential is to use stimuli with energy concentrated in a restricted frequency range around the frequency of interest (i.e., brief tones) rather than a broadband stimulus (i.e., a click). Brief tones have their peak energy at the nominal frequency of the tone and have sidebands of energy at lower and higher frequencies (Burkard, 1984; Durrant, 1983; Gorga and Thornton, 1989; Harris, 1978; Laukli, 1983;

Nuttall, 1981; Pfeiffer, 1974). Evoked potentials to these brief tones may be elicited by any of the frequencies present in the spectrum of the stimulus. This spread of energy to frequencies other than the nominal frequency is known as "spectral splatter" (Durrant, 1983). This spectral splatter can lead to spurious estimations of pure-tone behavioral thresholds in individuals with sloping high-frequency hearing losses (Davis, Hirsh, Popelka, and Formby, 1984; Picton, 1978; Picton, Ouellette, Hamel, and Smith, 1979; Purdy and Abbas, 1989; Stapells, 1984; Stapells et al., 1994, 1985) and in individuals with a reverse-slope or notched audiogram (Hayes and Jerger, 1982; Picton et al., 1979).

Brainstem responses in normal hearing subjects to nonmasked brief tones (500 to >4000 Hz) are frequency specific when the tones are presented at low and moderate stimulus intensities, that is, about 70 dB peak-to-peak equivalent (ppe) SPL or less (Beattie and Kennedy, 1992; Davis et al., 1984; Folsom, 1984; Jacobson, 1983; Klein, 1983; Picton et al., 1979; Stapells and Picton, 1981). Recordings to nonmasked stimuli at intensities above 70 dB ppe SPL, however, may contain contributions from frequencies above or below the test frequency due to the spread of energy away from the nominal frequency of the tone (Beattie and Kennedy, 1992; Burkard and Hecox, 1983; Folsom, 1984; Jacobson, 1983; Kileny, 1981; Klein, 1983; Picton et al., 1979; Stapells, 1984; Stapells and Picton, 1981). This may occur with 500-, 1000-, 2000- and/or 4000-Hz tones. Above 70 dB ppe SPL, there is also an increase in the upward spread of cochlear excitation, as demonstrated, for example, by VIIIth nerve tuning curve studies (e.g., Anderson, Rose, Hind, and Brugge, 1970; Rose, Hind, Anderson, and Brugge, 1971). Thus, the decreased frequency and place specificity of the nonmasked ABR (and MLR) to tonal

stimuli at high stimulus intensities is due to a combination of the increased spread of cochlear excitation seen for high stimulus intensities, as well as the effects of acoustic spectral splatter.

The decreased frequency and place specificity of evoked potentials to brief tones have been shown by studying latency and amplitude changes of ABR wave V for masked compared to nonmasked responses (Beattie and Kennedy, 1992; Burkard and Hecox, 1983; Kileny, 1981, Jacobson, 1983; Picton et al., 1979; Stapells, 1984; Stapells and Picton, 1981; Stapells et al., 1994, 1985). The latency effects have been most evident for the responses to the lower frequency tonal stimuli and have led to some controversy in the literature regarding the use of the ABR to 500-Hz brief tones for estimating low-frequency hearing sensitivity. A few studies have suggested that: (1) the ABR to high-intensity nonmasked 500-Hz tonal stimuli is primarily generated from the basal end of the cochlea; (2) waveform identification of the ABR to 500-Hz stimuli is problematic in quiet, and even more so in the presence of high-pass (HP) noise masking; and (3) ABR thresholds to 500-Hz stimuli have poor frequency specificity and thus are poor predictors of low-frequency behavioral thresholds (e.g., Davis and Hirsh, 1976; Laukli, 1983; Laukli, Fjermedal, and Mair, 1988; Laukli and Mair, 1986; Scherg and Volk, 1983; Sohmer and Kinarti, 1984; Weber, 1987). Contrary to these results, many studies have been successful in recording replicable and clearly identifiable ABRs to air-conducted 500-Hz stimuli both in quiet and in the presence of ipsilateral notched noise and/or HP noise masking, down through 55 dB ppe SPL and lower (Davis and Hirsh, 1979; Hyde, 1985; Hyde, Matsumoto, and Alberti, 1987; Jacobson, 1983; Kileny, 1981; Kodera, Yamane, Yamada, and Suzuki, 1977; Munnerley, Greville, Purdy, and Keith, 1991; Purdy, Houghton, Keith, and Greville, 1989; Stapells, 1984; 1989; Stapells and Picton, 1981; Stapells et al., 1995;

1994; 1990; Suzuki, Hirai, and Horiuchi, 1977; Suzuki, Kodera, and Yamada, 1984; Wu and Stapells, in preparation). In addition, high correlations (i.e., $\geq .9$) between ABR thresholds to 500-Hz air-conducted tones in notched noise and/or HP noise and 500-Hz pure-tone behavioral thresholds have been demonstrated for normal and hearing-impaired subjects (Kileny and Magathan, 1987; Munnerley *et al.*, 1991; Stapells *et al.*, 1995; 1990).

In view of the controversies regarding the use of the ABR to 500-Hz tones to estimate low-frequency hearing sensitivity, the MLR has been proposed as a better indicator of 500-Hz sensitivity (e.g., Kavanagh, Harker, and Tyler, 1984; Kileny and Shea, 1986; Musiek and Geurkink, 1981; Palaskas, Wilson, and Dobie, 1989; Scherg and Volk, 1983). The suggestion has been based upon the observation that larger peak-to-peak amplitudes are measured for the MLR compared to the ABR in response to 500-Hz tones, leading to better detectability of the MLR (Scherg and Volk, 1983; Wu and Stapells, 1994; Wu and Stapells, in preparation). A commonly held belief is that the MLR may be recorded using tones with longer rise times than the ABR without causing a significant decrease in the amplitude of the response. Tones with longer rise times have greater acoustic frequency specificity (Burkard, 1984; Gorga and Thornton, 1989; Jacobson, 1983; Stapells and Picton, 1981). The current literature on the effects of rise time on the MLR, however, shows significant decreases in MLR amplitude when rise times exceed 5 ms (Beiter and Hogan, 1973; Vivion, Hirsch, Frye-Osier, and Goldstein, 1980), similar to that reported for the ABR (e.g., Stapells and Picton, 1981).

To date, only three published studies have directly assessed the frequency specificity of the MLR to tonal stimuli (Mackersie, Down, and Stapells, 1993; Smith, Mills and Schmeidt, 1990; Wu and Stapells, 1994). These studies compared the frequency specificity of the ABR to the MLR

with the use of pure-tone masking paradigms. Smith and colleagues employed forward-masking of 2000-Hz probe tones with four gerbils and reported that the MLR is less frequency specific than the ABR, as indicated by frequency tuning curves which are similar in shape but wider in width for the MLR compared to the ABR, and by greater susceptibility of the MLR to masking (Smith et al., 1990). An opposite conclusion was reached by Stapells and colleagues (Mackersie et al., 1993; Wu and Stapells, 1994), who tested 8-12 human subjects with a simultaneous masking paradigm and reported no significant differences in the frequency specificity of the ABR and MLR to low-intensity (60 dB ppe SPL) 500- and 2000-Hz probe tones. The inconsistencies between the findings of Smith et al. and these two later studies may be related to the differences in masking techniques used, differences in adaptation characteristics for the ABR and MLR, and/or species differences in the generators of the MLR.

Recent studies by Stapells and colleagues (Mackersie et al., 1993; Wu and Stapells, 1994) show that the MLR is a reasonably frequency-specific measure for 60 dB ppe SPL 500- and 2000-Hz tones (Mackersie et al., 1993; Wu and Stapells, 1994). No published research, however, has addressed the question of how frequency specific the MLR is to higher intensity 500- and 2000-Hz tones. This information is clearly needed to determine the potential benefit of the MLR for threshold evaluations.

Currently, the most widely used tonal stimuli for recording evoked potentials are linear-gated brief tones. There are, however, a number of nonlinear gating functions (e.g., cosine, exponential, Gaussian, Hanning, Kaiser-Bessel, exact-Blackman) which can theoretically yield frequency spectra that are more narrow than those for linear-gated tones, while maintaining the rapid stimulus onset

needed for eliciting both the ABR and MLR (Gorga and Thornton, 1989; Harris, 1978; Nuttal, 1981). The differences between the linear and nonlinear stimuli are in the width of the main energy lobe, the amplitudes of the sidelobes of energy, and the rate of decay of the sidelobes with frequency.

Some investigators have claimed that the frequency specificity of the ABR will be improved by using a Blackman-gated tone (Gorga, Beauchaine, Kaminski, and Bergman, 1992; Gorga and Thornton, 1989; Telian and Kileny, 1989). If a 2000-Hz tonal stimulus with a five-cycle total duration is employed, the acoustic spectra of the exact-Blackman-gated stimuli have sidelobes of energy approximately 68 dB below the peak energy of the main lobe, an approximate 1773-Hz wide main energy lobe (at 20 dB below the peak energy), and a 6 dB/octave rolloff slope thereafter (Nuttal, 1981). In contrast, the linear-gated "2-1-2" cycle tone -- recommended for frequency-specific testing by Davis (1976) and by Davis, Hirsh, Popelka, and Formby, (1984) -- has energy in the sidelobes 27 dB below the amplitude of the main energy lobe, an approximate width of 1239 Hz for the main energy lobe (20 dB below the peak), and an 18 dB/octave slope thereafter. The reduction of energy in the sidelobes of the Blackman-gated tone may have the advantage of removing contributions to the evoked potentials from frequencies other than the nominal frequency and thus yield more frequency-specific responses than would have been obtained with a linear-gated signal (Gorga and Thornton, 1989). This may not be the case, however, as the wider main lobe of the exact-Blackman-gated tone likely stimulates a broader region of the basilar membrane. To date, no published studies in humans have investigated how these frequency spectra differences between the exact-Blackman- and linear-gated tones are reflected by either of these evoked potentials.

Several noise masking techniques have been used to investigate the frequency and place specificity of evoked potentials to different stimuli. These include: pure-tone masking (Folsom, 1984, Folsom and Wynne, 1987; Klein, 1983, Klein and Mills, 1981a,b; Mackersie et al., 1993; Wu and Stapells, 1994); notched-noise masking (Beattie and Kennedy, 1992; Jacobson, 1983, Picton et al., 1979; Stapells, 1984; Stapells and Picton, 1981); and the high-pass noise/derived response (HP/DR) technique (Don and Eggermont, 1978; Eggermont, 1976; Eggermont and Don, 1980; Kramer, 1992; Noursak and Stapells, 1992). The HP/DR technique yields the most frequency and place specific evaluation of a response due to its use of HP noise masking, where no downward spread of masking occurs resulting from the steep high-frequency edge of the travelling wave in the cochlea (Stapells et al., 1994; 1985).

In the HP/DR technique, the ABR and/or MLR to either clicks or tones is recorded in quiet and then simultaneously with broadband noise of sufficient intensity to completely mask the response. The evoked potential is then recorded in the presence of HP noise, and the response in HP noise at one cutoff frequency is subtracted from the response obtained in the presence of HP noise with a higher cutoff frequency. The result is a "derived response" to the frequencies between the two cutoff frequencies. The assumptions underlying this technique are that: (1) the HP masker prevents contributions to the responses from cochlear fibers with characteristic frequencies above the HP cutoff frequency, leaving those fibers with characteristic frequencies below the HP cutoff frequency unaffected; (2) the subtraction procedure yields "derived responses" which represent cochlear activity limited to the frequency regions between the two HP noise cutoff frequencies; and (3) the subtraction procedure is linear (i.e., that individual derived responses resulting from contributions of adjoining sections of the cochlea add up

to the nonmasked response). Studies by Don and Eggermont (1978), Evans and Elberling (1982), and Parker and Thornton (1978a,b) have provided evidence that these assumptions are valid.

Cochlear contributions to the derived responses may be assessed by plotting the amplitudes of the derived responses as a function of derived-band center frequency (Eggermont, Spoor, and Odenthal, 1976). The area below the response amplitude curve represents the frequency regions of the cochlea contributing to the nonmasked evoked potential. Derived response amplitude profiles may be determined for any frequency region along the cochlear partition, depending upon the spacing of the HP noise cutoff frequencies. Typically, one-octave-wide or half-octave-wide regions along the basilar membrane have been studied (Burkard and Hecox, 1983; Don and Eggermont, 1978; Don, Eggermont, and Brackmann, 1979; Eggermont, 1976; Eggermont and Don, 1980; Kramer, 1992; Noursak and Stapells, 1992; Ponton, Don, and Eggermont, 1992; Ponton, Eggermont, Coupland, and Winkelaar, 1992). The derived-band center frequencies which contain the maximum response amplitudes provide a measure of the frequency specificity of the evoked potential to the specific stimulus. The bandwidths (Hz) of these profiles are an additional measure of the frequency specificity of the evoked potential (e.g., Dauman, Cazals, and Aran, 1988; Mackersie et al., 1993; Portmann, Harrison, Negrevergne, Dauman, and Aran, 1983; Wu and Stapells, 1994).

At present, no published studies have directly assessed the cochlear contributions to the ABR or MLR in response to moderate- to high-intensity 500- and 2000-Hz air-conducted tones. Furthermore, no study in humans has been published which assesses whether the frequency spectrum differences between linear- versus nonlinear-gated tonal stimuli are reflected in either the ABR or the MLR. Using the HP/DR technique, the purposes of this study were therefore to assess: (1) the

frequency specificity and cochlear contributions to the ABR and MLR to 80 dB ppe SPL 500- and 2000-Hz tones; (2) the differences, if any, in the frequency and place specificity of the ABR (wave V) *versus* MLR (wave Na-Pa); and (3) the differences, if any, in the frequency and place specificity of these responses to exact-Blackman- *versus* linear-gated tones.

I. METHODS

A. Subjects

Twelve normal-hearing adults (4 males and 8 females) participated in this study. The age range of the subjects was 18-40 years of age, with a mean age of 27.25 years. All had behavioral pure-tone audiometric thresholds of 15 dB HL (ANSI, 1969) or better at octave frequencies of 250 through 8000 Hz in the test ear, and no significant otologic or neurologic histories. On each day of testing, type A tympanograms (220-Hz probe tone) and a present ipsilateral acoustic reflex to a 90 dB HL 1000-Hz tone were obtained.

B. Stimuli

The stimuli were generated and presented by a Neuroscan "STIM" system. The stimuli were 500- and 2000-Hz brief tones which were presented in two conditions: (1) "2-1-2" linear tones, consisting of a linear two-cycle rise and two-cycle fall time, and a plateau time of one cycle, and (2) exact-Blackman-gated tones, with a five-cycle total duration and no plateau (Harris, 1978, formula 32). Figure 1 displays the acoustic spectra of these stimuli. The stimuli were of alternating onset polarity and were presented at a rate of 9.4/s using Etymotic Research ER-2 insert earphones. The stimuli were presented to one ear per subject, randomly selected for each subject, and were presented at 80 dB ppe SPL. The 80 dB ppe SPL value corresponds to levels of 53 dB nHL for the 500-Hz stimuli and 52 dB nHL for the 2000-Hz stimuli, as determined from a pilot study conducted on 10 subjects with normal hearing.

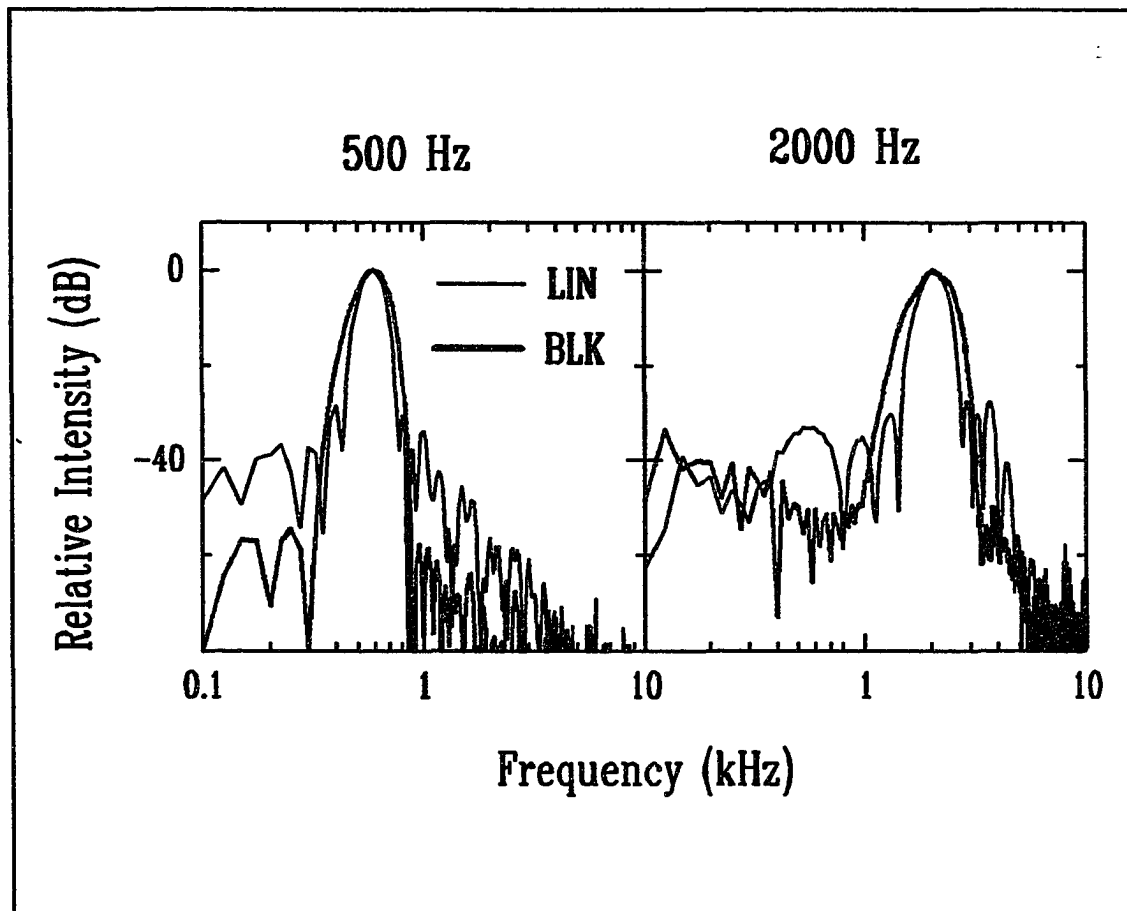


Figure 1. Acoustic spectra for exact-Blackman- versus linear-gated tones for 500 Hz (left) and 2000 Hz (right).

C. Broadband and HP Noise Masking

Broadband pink noise was generated by a white-noise masking module (Coulbourn model S81-02) and pink noise audio filter (Coulbourn S86-05), and then HP filtered by a Stanford Research System filter (model SR650, 115 dB/octave slope), and attenuated (Coulbourn S85-08). The intensity of the broadband pink noise required to mask the ABR and MLR to the 80 dB ppe SPL exact-Blackman- and linear-gated tones was initially determined behaviorally from a pilot study conducted on 10 normal-hearing adults. For each subject in the main study, the maximum of the masker intensity measured from the pilot group was increased in 1-dB

steps until the ABR and MLR was judged to be completely masked. The mean pink noise masker intensity employed in the main study was 92 dB SPL (range = 90 - 93 dB SPL).

The HP noise cutoff frequencies employed for the 500-Hz stimuli were: 4.0, 2.83, 2.0, 1.41, 1.0, 0.707, 0.5, 0.354, and 0.25 kHz; the HP-cutoff frequencies for the 2000-Hz stimuli were: 8.0, 5.66, 4.0, 2.83, 2.0, 1.41, 1.0, 0.707, and 0.5 kHz. The electrical frequency spectra of the broadband pink noise and the various HP noise conditions are displayed in Figure 2a.

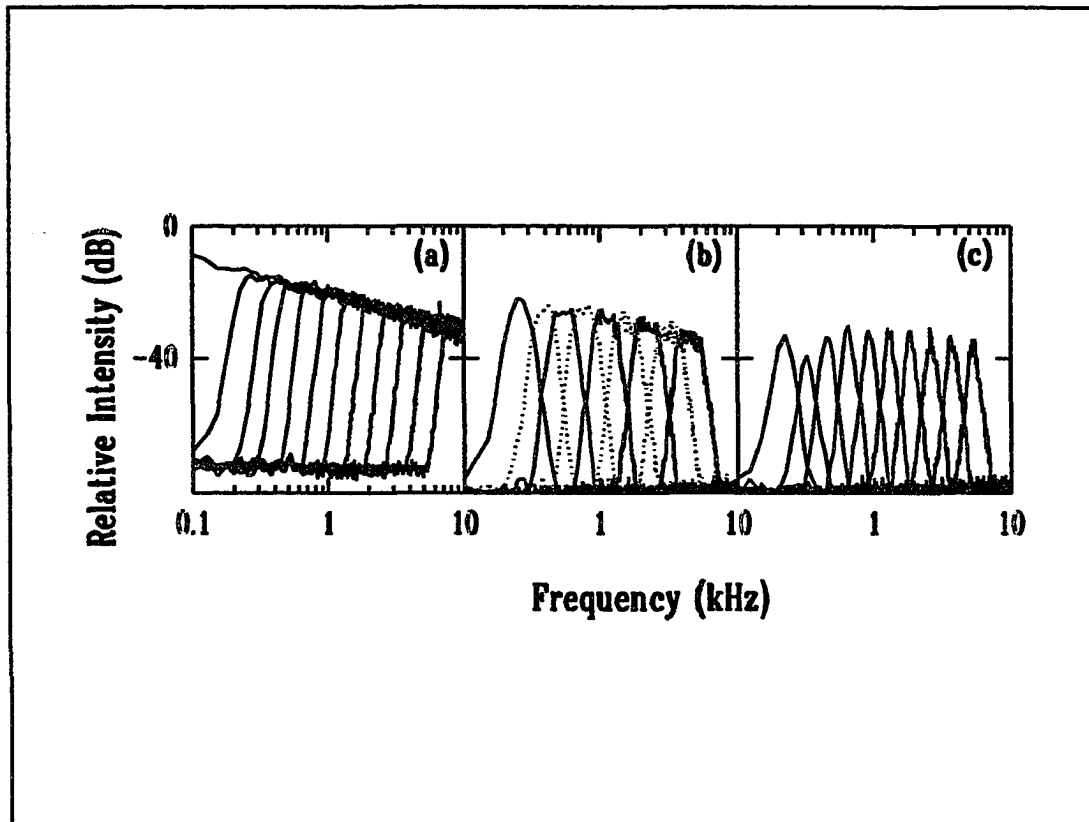


Figure 2. (a) Electrical spectra of pink noise and HP noise, (b) one-octave-wide derived bands obtained by subtraction of HP noise maskers separated by full octaves, (c) derived bands obtained by subtraction of HP noise maskers separated by half octaves.

D. Evoked Potential Recordings

All recordings and waveform analyses were carried out using the Neuroscan "SCAN" system. Simultaneous recordings of the ABR and MLR were obtained using gold-plated electrodes placed on the vertex (Cz) and earlobe (A1 or A2) of each subject, with a forehead electrode (Fpz) serving as ground. Interelectrode impedances were 2000 Ohms or less. The electroencephalographic (EEG) signals were amplified (gain = 100,000) and analog filtered (10-3000 Hz, 6 dB/octave, Grass Model 12). The EEG signals were digitized (12-bit converter) using a sampling rate of 12,128 Hz over an analysis time of 84 ms (including a pre-stimulus baseline of 3 ms), and stored as averages of 1000 trials each. Trials containing amplitudes exceeding $\pm 25 \mu\text{V}$ were automatically rejected. The calibration of the EEG amplifier was checked daily before each test session. The averaged responses were digitally filtered *post hoc* in the frequency domain (forward and inverse FFTs; data not windowed) using a HP filter setting of 20 Hz (24 dB/octave) and a low-pass (LP) filter setting of 1000 Hz (96 dB/octave). After digital filtering, average waveforms representing the overall average of 8000 sweeps were calculated, as were two replications of 4000 sweeps each and four replications of 2000 sweeps each.

E. Procedure

All testing was performed in a double-walled sound attenuating room (Industrial Acoustics Corporation). Subjects were seated in a reclining chair, resting or reading quietly during the testing. Subjects were instructed to remain awake during testing, and their EEG activity was monitored on an oscilloscope. Each subject participated in four test sessions of approximately 4.5 to 5 hours each. All of the subjects were tested with the exact-Blackman- and linear-gated stimuli at both 500 and

2000 Hz in quiet and simultaneously with broadband pink noise, and the nine HP noise cutoff frequency conditions. Each stimulus frequency was tested over two sessions with the HP noise conditions being presented in a different order for the second session. Four replications of 1000 sweeps each were collected within a test session yielding a total of 8000 sweeps for the nonmasked, broadband noise and HP noise conditions for each stimulus. The orders of the stimulus test frequencies, linear versus nonlinear stimuli, and the HP noise cutoff frequencies, were all randomized for each subject.

F. Derived Responses

Narrowband derived responses were obtained by subtracting, in succession, individual recordings of the response to the tone in HP noise at one cutoff frequency from the response to the same frequency tone recorded in HP noise at a higher cutoff frequency. This technique was applied to determine the one-octave-wide and half-octave-wide contributions to the evoked potentials. The HP/DR subtraction procedure resulted in seven separate derived responses for full-octave analyses, and eight derived responses for half-octave analyses. Only responses to the various HP noise conditions recorded within one test session were subtracted from each other to obtain the derived responses.

For clarity of presentation in this paper, the center frequency (CF) of the derived responses, labeled "nominal" CF, is the frequency of the lower of the two HP cutoff frequencies used in the subtraction (Don *et al.*, 1979). The actual center frequencies of the narrowband regions contributing to the full- and half-octave responses can be estimated from the acoustic noise spectra. An estimate of the derived band was obtained by subtracting the spectrum of the HP noise at one cutoff frequency from the spectrum of the HP noise at the higher cutoff

frequency (Don and Eggermont, 1978; Noursak and Stapells, 1992). Figures 2b and 2c represent estimates of the full-octave and half-octave derived bands, respectively. The calculated CFs for the derived bands for the full- and half-octave analyses are displayed in Table 1 and are close to the "nominal" CFs.

Table 1. Nominal and Calculated Derived-Band Center Frequencies (kHz)

500-Hz TONES

Full-Octave Derived-Band Center Frequencies

Nominal 2.0, 1.410, 1.0, 0.707, 0.50, 0.354, 0.25

Calculated 2.2, 1.525, 1.1, 0.775, 0.55, 0.425, 0.25

Half-Octave Derived-Band Center Frequencies

Nominal 2.83, 2.00, 1.41, 1.00, 0.707, 0.50, 0.354, 0.25

Calculated 2.675, 1.875, 1.325, 0.925, 0.65, 0.45, 0.325, 0.225

2000-Hz TONES

Full-Octave Derived-Band Center Frequencies

Nominal 4.00, 2.83, 2.00, 1.41, 1.00, 0.707, 0.50

Calculated 4.575, 3.10, 2.20, 1.525, 1.10, 0.775, 0.55

Half-Octave Derived-Band Center Frequencies

Nominal 5.66, 4.00, 2.83, 2.00, 1.41, 1.00, 0.707, 0.50

Calculated 5.40, 3.68, 2.68, 1.88, 1.33, 0.93, 0.650, 0.45

G. Response Identification

Each subject's ABR/MLR waveforms were combined into waveform sets. A set of ABR/MLR waveforms included the overall average (8000 trials), two replications of 4000 trials each, and four replications of 2000 trials each. Each set was plotted out on a -3 to 81 ms time window for each stimulus in the quiet, broadband noise, nine HP noise conditions, and 15 derived-response conditions (seven full-octave and eight half-octave), resulting in 104 sets of waveforms per subject.

The decision regarding the presence or absence of ABR wave V and MLR wave Pa was made by combining the ratings of three judges experienced in the identification of ABRs and MLRs to tonal stimuli. Each judge was given a printout of a set of ABR and MLR waveforms for the nonmasked stimulus as well as for each of the HP noise cutoff frequency conditions and all of the derived response conditions. The derived response conditions were rated separately from the HP noise conditions. All three judges had knowledge of the frequency of the stimulus, however, they were blind to the type of stimulus (exact-Blackman- versus linear-gated tone), the HP noise cutoff frequency, and the center frequency of the derived response. The order of rating the various HP noise and derived response conditions, as well as the order of the subjects, were randomized for each rater. Each rater scored the ABR and MLR waveforms independently of the other raters.

In order to ensure agreement between the three judges, interjudge agreement was assessed in a pilot study with these judges on a large set of ABR/MLR waveforms. This set included responses to 500- and 2000-Hz tonal stimuli, and did not include any of the waveforms in the current study. These judges assigned the same score (using a 4-point scale) to these pilot responses approximately 70% of the time for waves V and Pa, and were within one rating category at least 90% of the time for these

evoked potentials. In the thesis study, the three judges showed high interjudge reliability, with Gamma probabilities ranging from .844 to .922.

H. Response Criteria

Each of the raters independently assigned a score of "1" to "4" to ABR wave V and MLR wave Pa in the grand average for the various HP noise and derived response conditions. The significance of the scores was as follows: a score of "4" indicated a "definite response", a "3" indicated a "probable response", a "2" indicated a "probable no-response", and a "1" indicated "definite no response". The raters were instructed to rate each peak separately and therefore might have assigned different scores for the specific peaks in the response. The three raters' scores were averaged and this average was then rounded off to the nearest integer for each of the waveform peaks. Waveform peaks with a mean score (across the three raters) of "3-4" were judged as responses, and those with a mean score of "1-2" indicated no response (Stapells, 1984; Stapells *et al.*, 1990).

I. Response Measurements

Amplitude measures for each subject were obtained from the grand averages (8000 trials) for those ABR wave V and MLR wave Pa peaks having a mean rating of 3 or 4 in the various HP noise masking and derived response conditions. The peak-to-peak amplitude measures taken were V-V' and Na-Pa. Peaks judged as no response, as determined by a mean rating of less than 2.5, were assigned an amplitude value of zero μV . In a few conditions, all subjects showed waveforms with absent responses (e.g., ABR to 2000-Hz tones masked by 500-Hz high-pass noise), therefore resulting in group standard deviations equal to zero. Although these

infrequent zero standard deviations may have introduced some artifact into the ANOVA F values, it is unlikely they had any major impact on the results.

Wave V was defined as the maximum vertex-positive peak occurring between 6 and 20 ms following stimulus onset. If several peaks of equal amplitude occurred within this range, the peak preceding the largest negative shift was selected. Wave V' was defined as the greatest negativity within 8 ms after wave V (Stapells and Picton, 1981; Noursak and Stapells, 1992). MLR wave Na was defined as the largest negativity following wave V and occurring between 10 and 30 ms; wave Pa was the largest positivity following wave Na and occurring between 20 and 50 ms.

Mean peak-to-peak amplitudes (ABR V-V' and MLR Na-Pa) were plotted as a function of HP noise cutoff frequency and as a function of derived-band center frequency to form response amplitude profiles. Separate ABR and MLR amplitude profiles were constructed for each stimulus frequency, for each stimulus type (exact-Blackman- versus linear-gated tones), and for the full- and half-octave derived responses.

Each subject's absolute ABR wave V and MLR wave Pa latencies were measured from the nonmasked responses to the 500- and 2000-Hz exact-Blackman- and linear-gated tones as well as from those HP-noise-masked responses judged to contain replicable peaks. Latency measurements for waves V and Pa were also obtained from the full- and half-octave derived responses whose "nominal" CFs were equal to the frequencies of the stimuli. The latency values were corrected for the delays introduced by the insert earphones.

J. Summary Statistics

Two summary statistics were calculated from the individual subjects' derived response amplitude profiles: (1) the center frequency

(Hz) of the profile, and (2) the bandwidth (Hz) of the amplitude profile at a relative amplitude of 50 percent. Second-order polynomial linear regression analyses were fit to each subject's derived response amplitude profiles in order to calculate these measures. Each measure was calculated for ABR wave V-V' and MLR wave Na-Pa profiles for both the exact-Blackman- and linear-gated tones. These summary statistics were determined separately for the full- and half-octave amplitude profiles.

K. Statistical Analyses

Peak-to-peak amplitudes and latencies were analyzed using descriptive statistics and repeated measures analyses of variance (ANOVAs). The summary statistics described above were also analyzed using repeated measures ANOVAs. Results for the full- and half-octave derived response profiles were analyzed independently. Greenhouse-Geisser epsilon corrections for the degrees of freedom for repeated measures were employed when appropriate (Greenhouse and Geisser, 1959). Results were considered statistically significant if $p < .01$. When significant results were found in the ANOVAs, Newman-Keuls *post hoc* tests were performed to determine the pattern of the significant differences. Results of these *post-hoc* analyses were considered significant at $p < .05$.

II. RESULTS

A. Nonmasked Responses

Figure 3 displays the grand mean ($N=12$) nonmasked ABRs and MLRs recorded to 80 dB ppe SPL 500- and 2000-Hz exact-Blackman- and linear-gated tones. ABR wave V, and MLR waves Na, Pa, and Nb are labeled.

Table 2 contains the mean absolute latencies and peak-to-peak amplitude values for these nonmasked responses. Three-way repeated measures ANOVAs (stimulus frequency $\times$ wave $\times$ window) were calculated on the latency and amplitude results for the quiet condition. The peak-to-peak amplitude of MLR Na-Pa is significantly larger compared to the amplitude of ABR V-V' [$F(1,11)=35.58$, $p < .001$]. There are no statistically significant differences between the amplitudes of responses to the exact-Blackman- versus linear-gated tones [$F(1,11)=0.82$, $p=.385$], or to the 500- versus 2000-Hz tones [$F(1,11)=2.65$, $p=.132$]. There are no statistically significant interactions [frequency $\times$ window: $F(1,11)=2.11$, $p=.174$; wave $\times$ window: $F(1,11)=0.50$, $p=.496$; frequency $\times$ wave $\times$ window: $F(1,11)=4.99$, $p=.047$]. Although not statistically significant, there is a trend for wave Na-Pa to be slightly larger to the 500-Hz stimuli compared to the 2000-Hz tones [frequency $\times$ wave: $F(1,11)=9.17$, $p=.012$].

The results of the ANOVA on the latencies revealed expected significant main effects for stimulus frequency [$F(1,11)=143.07$, $p < .0001$] and wave [$F(1,11)=4836.66$, $p < .0001$], with later latencies for the responses to the 500-Hz stimuli and for MLR wave Pa. There is also a significant latency difference between the exact-Blackman- versus linear-gated tones [window: $F(1,11)=27.42$, $p < .001$], with the responses to the exact-Blackman-gated tones having a longer latency.

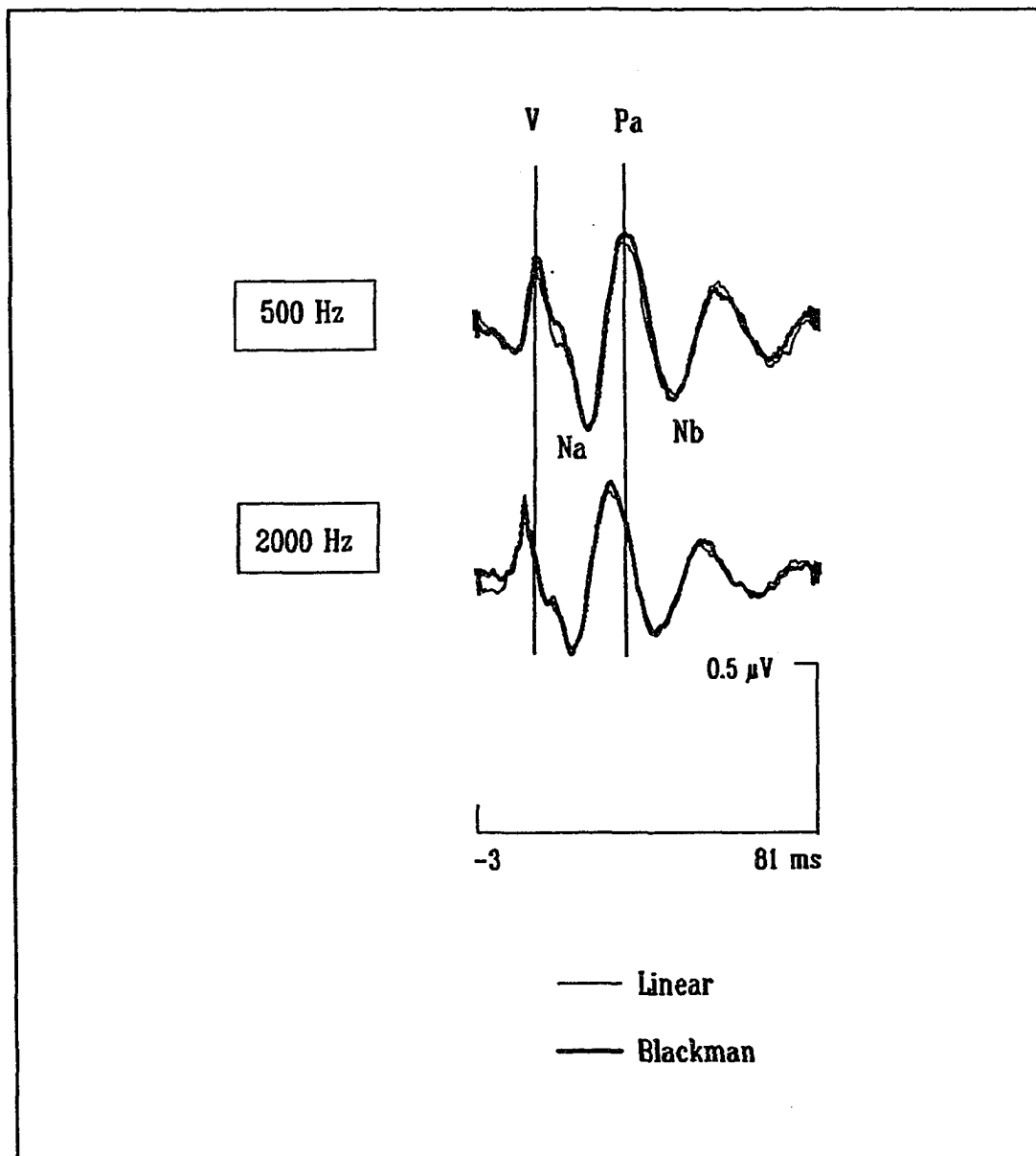


Figure 3. Grand mean (N=12) nonmasked waveforms recorded to 80 dB peak-to-peak equivalent (ppe) SPL 500- and 2000-Hz exact-Blackman-versus linear-gated tones. These evoked potentials are the average of a total of 96,000 trials (8000 trials per subject).

No interactions (frequency x wave: $F(1,11)=4.58$, $p=.056$; frequency x window: $F(1,11)=0.48$, $p=.503$; window x wave: $F(1,11)=0.01$, $p=.915$; frequency x window x wave: $F(1,11)=5.8$, $p=.035$] reached statistical significance.

Table 2. Mean absolute latencies (ms) and peak-to-peak amplitudes (μV) for ABR V and MLR Pa to 80 dB ppe SPL 500- and 2000-Hz nonmasked tones.

	500 Hz				2000 Hz			
	<u>ABR V</u>		<u>MLR Pa</u>		<u>ABR V</u>		<u>MLR Pa</u>	
	Linear ¹	Blk ²	Linear	Blk	Linear	Blk	Linear	Blk
Latency ³	9.91	10.84	31.97	32.31	7.08	7.29	27.88	28.62
SD	0.96	0.83	1.57	1.21	0.34	0.60	1.16	1.49
Amplitude ⁴	0.36	0.40	0.65	0.67	0.41	0.37	0.55	0.57
SD	0.10	0.12	0.20	0.23	0.12	0.08	0.17	0.18
¹ Linear = Linear-gated tones ² Blk = exact-Blackman-gated tones ³ Absolute latency values have been corrected for ER-2 insert earphone delay ⁴ ABR V-V' and MLR Na-Pa peak-to-peak amplitudes								

B. HP Noise Masking

The grand mean waveforms recorded to 80 dB ppe SPL 500- and 2000-Hz exact-Blackman- and linear-gated tones for the nine HP noise masking conditions are displayed in Figure 4. In response to the 500-Hz tones, clear ABRs and MLRs are present in each of the HP noise masking conditions down through 707 Hz, with no responses present at the lowest HP noise cutoff frequencies (i.e., 500, 354 and 250 Hz). For the 2000-Hz

stimuli, ABR wave V and MLR wave Pa are clearly evident down to a HP noise masking cutoff frequency of 2830 Hz and both waves disappear at cutoff frequencies of 1410 Hz and below. MLR wave Pa is present in the recordings obtained in the presence of HP noise with a 2000-Hz cutoff, however, there is no clear wave V. There are no obvious differences in the responses to the exact-Blackman- versus linear-gated tones at either stimulus frequency.

The ABRs and MLRs recorded in the presence of HP noise masking are smaller in amplitude and longer in latency than the nonmasked responses. The decrease in amplitudes and increase in latencies are evident even at the highest HP noise cutoff frequency for each stimulus frequency (i.e., 4000 Hz for the 500-Hz tones, and 8000 Hz for the 2000-Hz tones). The responses then remain essentially unchanged as the cutoff frequency of the masking noise is lowered until within a half octave of the nominal stimulus frequencies. These changes in response amplitudes and latencies with the introduction of the HP noise at the highest cutoff frequencies are probably due to low-level broadband noise masking resulting from the input broadband noise intensity (mean = 92 dB SPL) being higher than the maximum stopband attenuation of the HP filter (nominal = 80 dB SPL) (see Figure 2a). A central masking effect from the high-frequency noise may also explain some of the decrement. The decrease in amplitude is especially evident for the responses recorded to the 2000-Hz tones.

Amplitudes for the responses recorded in HP noise were normalized to a percentage of their nonmasked amplitudes. Mean normalized ABR V-V' and MLR Na-Pa amplitudes (and standard deviations) are plotted in Figure 5 as a function of HP noise cutoff frequency. There is little or no change in the amplitudes of waves V-V' and Na-Pa as the cutoff frequency of the HP noise is lowered until there is a sharp dropoff in the amplitude of the responses. The normalized amplitudes of ABR V-V' and

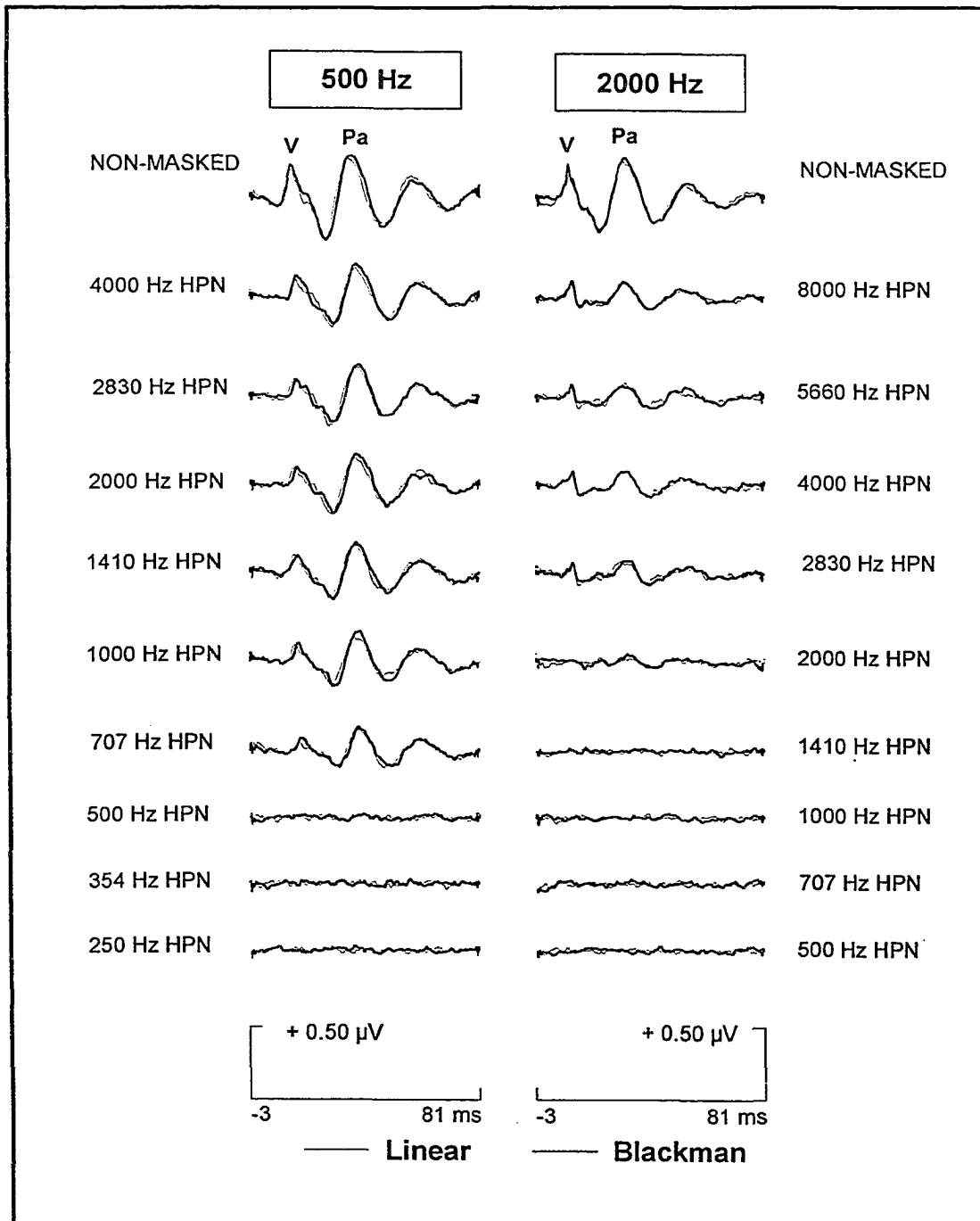


Figure 4. Grand mean (N=12) waveforms recorded to 80 dB ppe SPL 500- and 2000-Hz exact-Blackman- and linear-gated tones recorded in 9 HP noise conditions.

MLR Na-Pa to the 2000-Hz stimuli are lower (in percent) than those for the 500-Hz tones. This is especially evident for MLR Na-Pa, as indicated by a significant main effect for wave shown at this stimulus frequency (see Table 3). The low-level broadband masking effect, resulting from broadband noise being passed by the HP filter, is greater for the responses to the 2000-Hz tones compared to the responses to the 500-Hz stimuli, as well as for the MLRs versus the ABRs to the high-frequency tones, as shown in Figure 4.

Three-way repeated measures ANOVAs were calculated separately for the 500- and 2000-Hz amplitude profiles for the HP noise conditions. The results of these ANOVAs, detailed in Table 3, reveal a significant main effect for HP noise cutoff frequency for both the 500- and 2000-Hz stimuli. Neuman-Keuls *post-hoc* testing of the amplitude profiles for the 500-Hz tones reveal the ABRs and MLRs recorded at HP noise cutoff frequencies of 1000-4000 Hz are significantly larger in amplitude than those recorded at cutoff frequencies of 707 Hz and below. *Post hoc* comparisons of the amplitude profiles for 2000-Hz tones show that the main effect for HP noise cutoff frequency is due to fact the that waves V-V' and Na-Pa recorded at cutoff frequencies of 2830-8000 Hz have significantly larger normalized amplitudes than those recorded at cutoff frequencies of 2000 Hz and below. The amplitudes for the nonmasked condition were excluded in these *post-hoc* analyses. The results of the *post-hoc* analyses suggest that there is little contribution of stimulus energy from the frequencies higher than the nominal frequencies to the ABRs and MLRs to the 80 dB ppe SPL 500- and 2000-Hz tones. The percentage of the nonmasked amplitude of ABR wave V-V' to the 2000-Hz stimuli is significantly larger than for MLR wave Na-Pa (indicating a greater effect of the low-level broadband masking or greater central

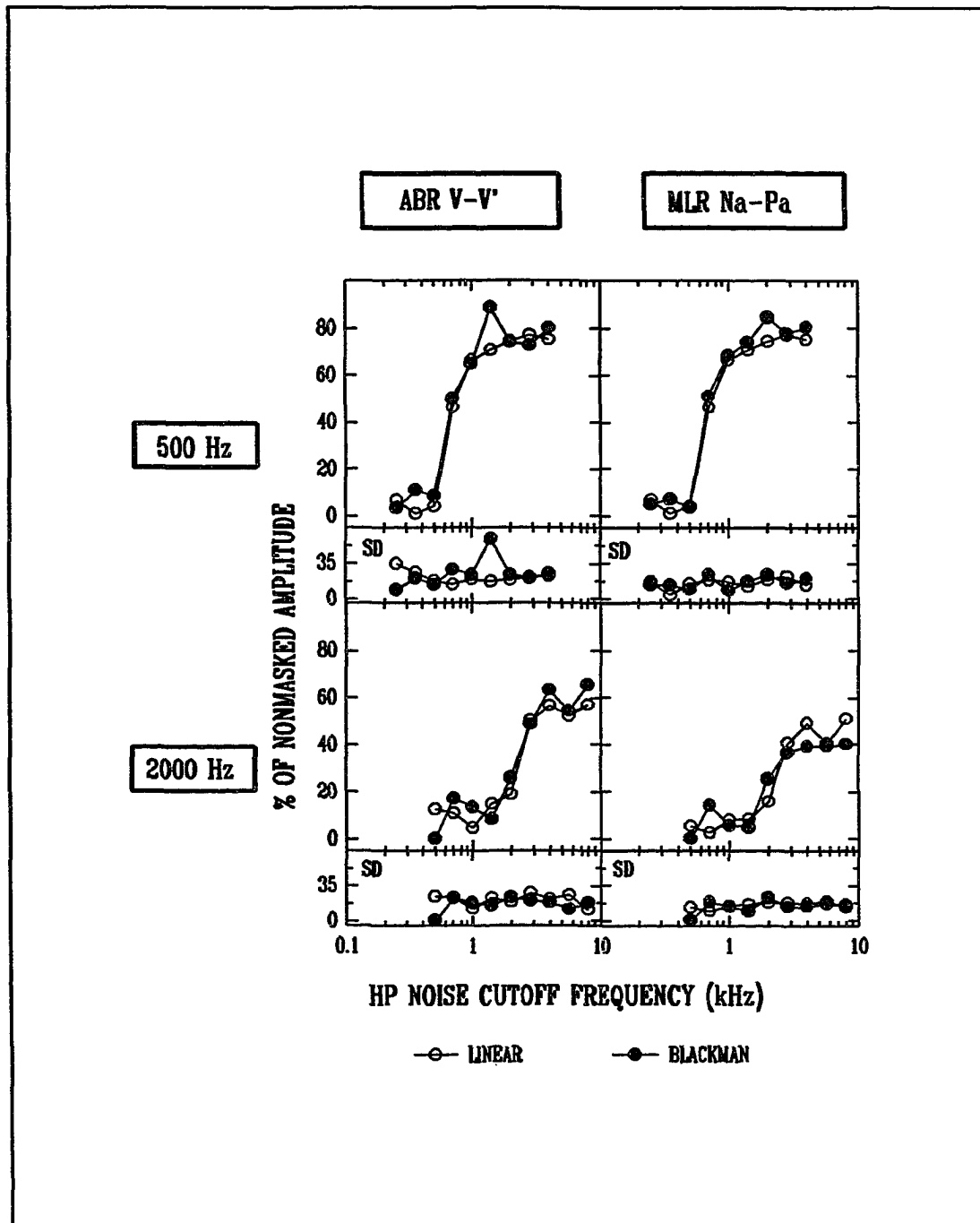


Figure 5. Mean and standard deviation (SD) response amplitude profiles for ABR wave V-V' and MLR wave Na-Pa to 500- and 2000-Hz exact-Blackman- versus linear-gated tones recorded in the HP noise masking conditions.

masking, on the MLR to the 2000-Hz tones). However, there is no significant HP noise x wave interaction, demonstrating that there is no difference in the frequency specificity of these evoked potentials. There are no significant differences between the amplitude profiles for responses to exact-Blackman- versus linear-gated tones for either stimulus frequency, nor any significant interactions. Both the ABR and MLR in response to the 2000-Hz tones decrease more by masking compared to the responses to the 500-Hz tones, however, this difference was not statistically tested. These findings show that there are no significant differences in the frequency specificity of the ABR versus the MLR, or in the responses to exact-Blackman- versus linear-gated tones. These results also suggest that the responses to the 500- and 2000-Hz tones are equally place specific. Significant changes in response amplitudes to both frequencies only occur within a half octave of the nominal stimulus frequencies.

Each subject's latencies for ABR wave V and MLR wave Pa were measured in the various HP noise conditions. Mean absolute latency values for the 500- and 2000-Hz stimuli are plotted as a function of the cutoff frequency of the HP noise in Figure 6. Each symbol in the figure represents a minimum of 10 subjects' data for the responses to the 500-Hz tones and 11 subjects' data for the responses to the 2000-Hz tones. The absolute latencies of waves V and Pa are longer to the 500-Hz tones compared to the 2000-Hz tones. The absolute latencies of waves V and Pa remain essentially unchanged as the cutoff frequency of the HP noise is lowered, until the HP noise cutoff reaches within approximately a half to one octave above the stimulus nominal frequency. The increases in latency are greater for the responses to the 500-Hz stimuli compared to the responses to the 2000-Hz tones, reflecting the longer travel time to reach the apical region of the cochlea.

Table 3. Results of 3-way Repeated Measures Analyses of Variance for Amplitude Profiles for the HP Noise Conditions

500 Hz							2000 Hz					
Source of Variance	df	G-G Epsilon Corrections ¹	Sums of Squares	Mean Squares	F	P ²	df	G-G Epsilon Corrections	Sums of Squares	Mean Squares	F	P ²
Wave	1		11.03	11.03	0.01	0.923	1		7210.27	7210.27	11.71	0.006*
Error Term	11						11					
Window	1		1095	1095	1.59	0.234	1		2.49	2.49	0.01	0.945
Error Term	11						11					
HP Noise Cutoff												
Frequency (CF)	8		381396	47674	114.24	0.0*	8		166124	20765	45.25	0.0*
Error Term	88	0.3216					88	0.4211				
Wave x Window	1		2.45	2.45	0.00	0.958	1		389.90	389.90	1.97	0.188
Error Term	11						11					
Wave X HP Noise CF	8		5229	653.70	2.97	0.028	8		3105	388.23	2.57	0.056
Error Term	88	0.5182					88	0.4605				
Window x HP Noise CF	8		4961	620.24	1.53	0.223	8		3286	410.83	1.19	0.326
Error Term	88	0.4030					88	0.5640				
Wave x Window x HP Noise CF	8		2784	348.11	1.21	0.32	8		2242	280.36	1.74	0.163
Error Term	88	0.4084					88	0.4653				

¹ Greenhouse-Geisser (G-G) epsilon corrections for degrees of freedom for repeated measures

² Probabilities after G-G epsilon corrections

* p < .01

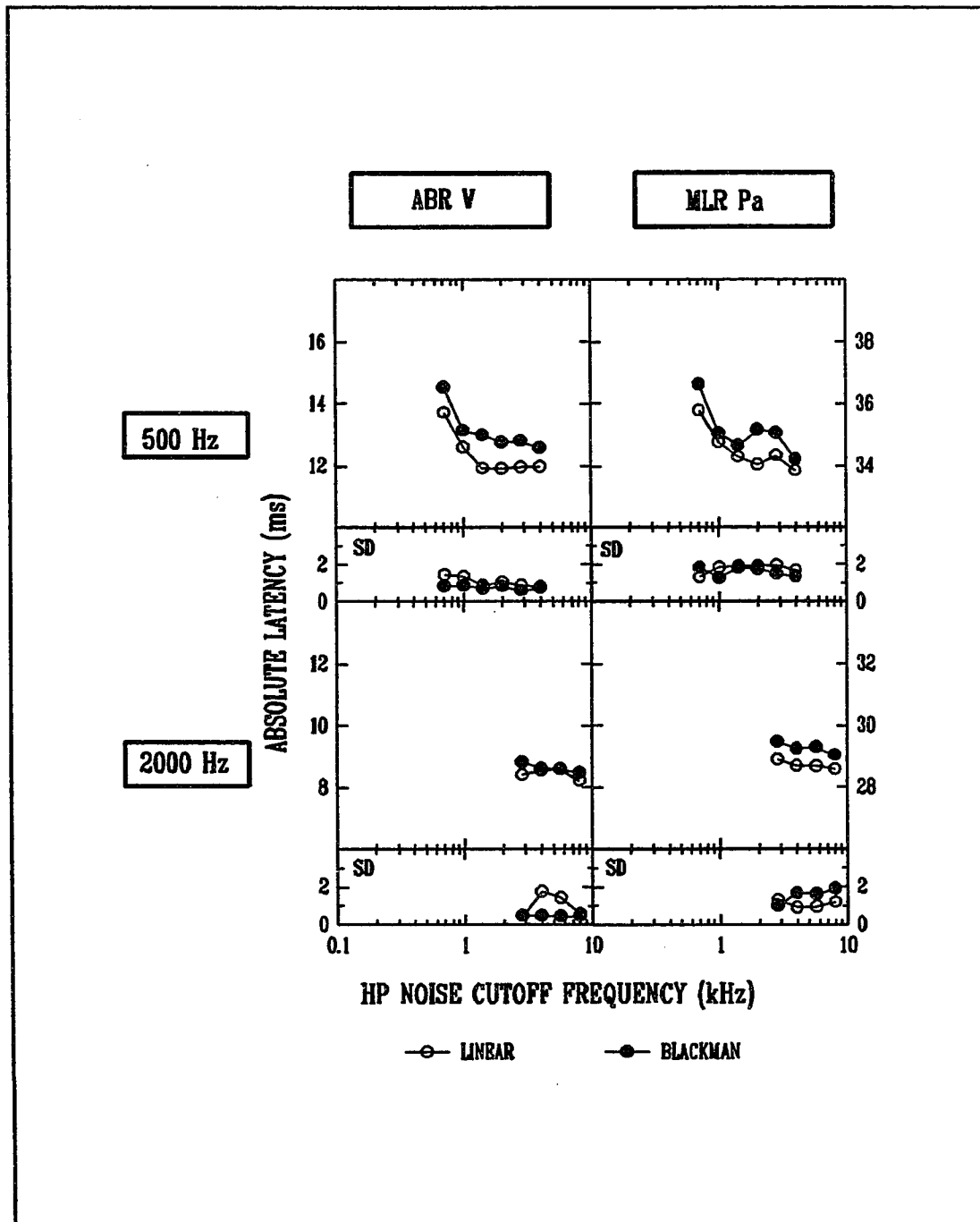


Figure 6. Mean waves V and Pa absolute latencies and standard deviations (SD) to the 500- and 2000-Hz stimuli as a function of HP noise cutoff frequency. Each symbol represents a minimum of 10 subjects for the 500-Hz tones and 11 subjects for the 2000-Hz tones.

Latency data for responses to each stimulus frequencies were analyzed in a similar manner (i.e., down to within one half octave above the nominal stimulus frequency). Responses at lower HP cutoff frequencies were few and thus were not included. Specifically, the HP noise cutoff frequencies analyzed for the 500-Hz stimuli were from 707 to 4000 Hz; the cutoff frequencies evaluated for the 2000-Hz tones were from 2830 to 8000 Hz. Separate three-way repeated measures ANOVAs were carried out on the absolute latency values from 10 subjects' responses to the 500-Hz tones and eight subjects' responses to the 2000-Hz tones. The remaining subjects' data were excluded from the analyses because their waveforms did not contain replicable responses to the exact-Blackman- and/or linear-gated tones in the lowest HP noise conditions included in the analyses (i.e., 707 Hz for the 500-Hz tones; 2830 Hz for the 2000-Hz tones). The results of the ANOVAs, shown in Table 4, reveal an expected significant main effect for wave for both stimulus frequencies, with longer latencies for MLR wave Pa. A significant main effect is seen for HP noise cutoff frequency for the 500-Hz stimuli only. *Post hoc* comparisons reveal that the latencies of the responses recorded to the 500-Hz tones in the presence of 707 and 1000 Hz HP noise masking are significantly longer than those recorded in HP noise with higher cutoff frequencies (i.e., 1410-4000 Hz). Small but nonsignificant latency increases are seen for the responses to the 2000-Hz tones as the cutoff frequency of the HP noise is lowered. The results of the ANOVAs also demonstrate that the latencies of the responses to the exact-Blackman-gated tones are significantly longer in comparison to the responses to the linear-gated tones. No interactions reached statistical significance for either of the stimulus frequencies.

Table 4. Results of 3-way Repeated Measures Analyses of Variance for the Absolute Latency of Waves V and Pa in HP Noise Masking

500 Hz							2000 Hz					
Source of Variance	df	G-G Epsilon Corrections ¹	Sums of Squares	Mean Squares	F	P ²	df	G-G Epsilon Corrections	Sums of Squares	Mean Squares	F	P ²
Wave	1		29255	29255	3222	0.0*	1		13667	13667	3994	0.0*
Error term	9						7					
Window	1		29.41	29.41	18.52	0.002*	1		15.72	5.72	16.26	0.005*
Error Term	9						7					
HP Noise Cutoff Frequency (CF)	5		93.52	18.70	31.47	0.0*	3		0.59	0.2	0.48	0.61
Error Term	45	0.4778					21	0.5944				
Wave x Window	1		0.46	0.46	0.46	0.516	1		3.35	3.35	3.49	0.104
Error Term	9						7					
Wave X HP Noise CF	5		2.18	0.44	0.76	0.539	3		0.75	0.25	1.52	0.248
Error Term	45	0.6778					21	0.7959				
Window x HP Noise CF	5		4.27	0.85	1.77	0.167	3		0.45	0.15	0.39	0.763
Error Term	45	0.6916					21	0.8415				
Wave x Window x HP Noise CF	5		2.31	0.46	0.84	0.484	3		0.26	0.09	0.31	0.773
Error Term	45	0.5914					21	0.7845				

¹ Greenhouse-Geisser (G-G) epsilon corrections for degrees of freedom for repeated measures

² Probabilities after G-G epsilon corrections

* p < .01

Overall, the mean amplitude and latency profiles for the responses recorded in HP noise indicate that ABR V-V' and MLR Na-Pa to moderately intense (80 dB ppe SPL) exact-Blackman- and linear-gated tones are frequency and place specific. Assuming contributions from frequencies lower than the tones' nominal frequencies are equal to or less than those from higher frequencies, cochlear contributions to these responses come from narrow regions along the basilar membrane (i.e., within one half to one octave of the nominal stimulus frequency). There are no significant differences in the frequency and place specificity of the ABR versus MLR or the responses to exact-Blackman- versus linear-gated tones. Contributions from frequency regions below, as well as at and above the tones' nominal frequencies are assessed by the derived responses.

C. Full-Octave Derived Responses

Figure 7 presents the grand mean derived response waveforms representing one-octave-wide regions along the basilar membrane for the exact-Blackman- and linear-gated tones at both stimulus frequencies. The largest amplitudes of ABR wave V-V' and MLR wave Na-Pa to the 500-Hz tonal stimuli are located in the responses in the 500-Hz derived band. Waves V and Pa are also present in the derived bands a half octave above and below this nominal test frequency. The largest amplitudes for waves V and Pa to the 2000-Hz stimuli are in the responses from the 1410- and 2000-Hz derived bands. ABRs and/or MLRs are inconsistently present to either the 500- or 2000-Hz tones in the other derived bands.

Peak-to-peak amplitudes of waves V-V' and Na-Pa were measured for each subject's derived responses. Because of the low-level broadband masking effect (discussed in Section B), each subject's amplitude values were normalized to a percentage of the amplitudes of their waves V-V'

and Na-Pa recorded in the highest HP noise masking condition (i.e., 4000 Hz for the 500-Hz stimuli, and 8000 Hz for the 2000-Hz stimuli). The mean relative amplitude values for ABR V-V' and MLR Na-Pa are plotted in Figure 8 as a function of derived-band center frequency for each stimulus frequency and for each stimulus envelope. The largest peak in the mean amplitude profiles for the 500-Hz stimuli occurs at 500 Hz for waves V-V' and Na-Pa for both the exact-Blackman- and linear-gated tones. The largest peak in the mean amplitude profiles for the 2000-Hz stimuli occurs at 2000 Hz for ABR V-V' for both stimuli. For MLR Na-Pa, the largest amplitude occurs at 2000 Hz for the linear tone and 1410 Hz for the exact-Blackman tone. There are cochlear contributions to both of these responses from one half to one octave above and below the two nominal stimulus frequencies. For individual subjects, the largest peak in the derived response ABR and MLR amplitude profiles for the 500-Hz exact-Blackman- and linear-gated tones were seen within a half octave of the nominal stimulus frequency for 11 out of 12 subjects. For the 2000-Hz tones, at least nine out of 12 subjects showed maximum derived response ABR and MLR amplitudes for both the exact-Blackman- and linear-gated tones within a half octave of the stimulus frequency.

Three-way repeated measures ANOVAs were calculated separately for the 500- and 2000-Hz derived response amplitude profiles. These results, displayed in Table 5, show the expected significant main effects for derived-band center frequency for the 500- and 2000-Hz tones. There are no significant differences, however, between results for ABR versus MLR, exact-Blackman- versus linear-gated tones, nor any significant interactions at either stimulus frequency. These results demonstrate that the ABR and MLR are equally frequency specific and that there are no significant differences in the frequency specificity of these evoked potentials to exact-Blackman- versus linear-gated tones.

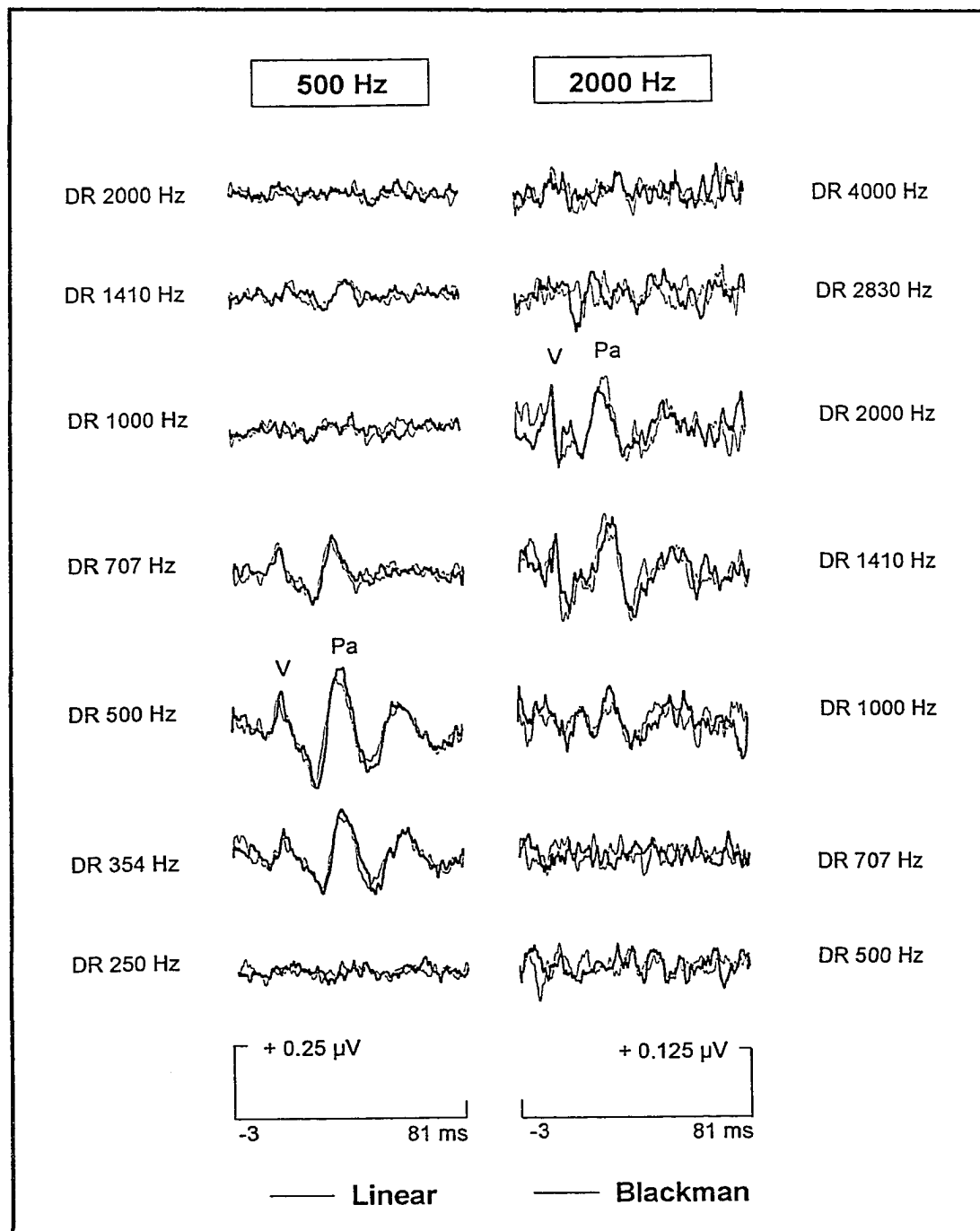


Figure 7. Grand mean (N=12) full-octave derived response waveforms to 80 dB ppe SPL exact-Blackman- and linear-gated 500- and 2000-Hz tones. Amplitude scale is +0.25 μ V for responses to 500-Hz tones (left) and +0.125 μ V for responses to 2000-Hz tones (right).

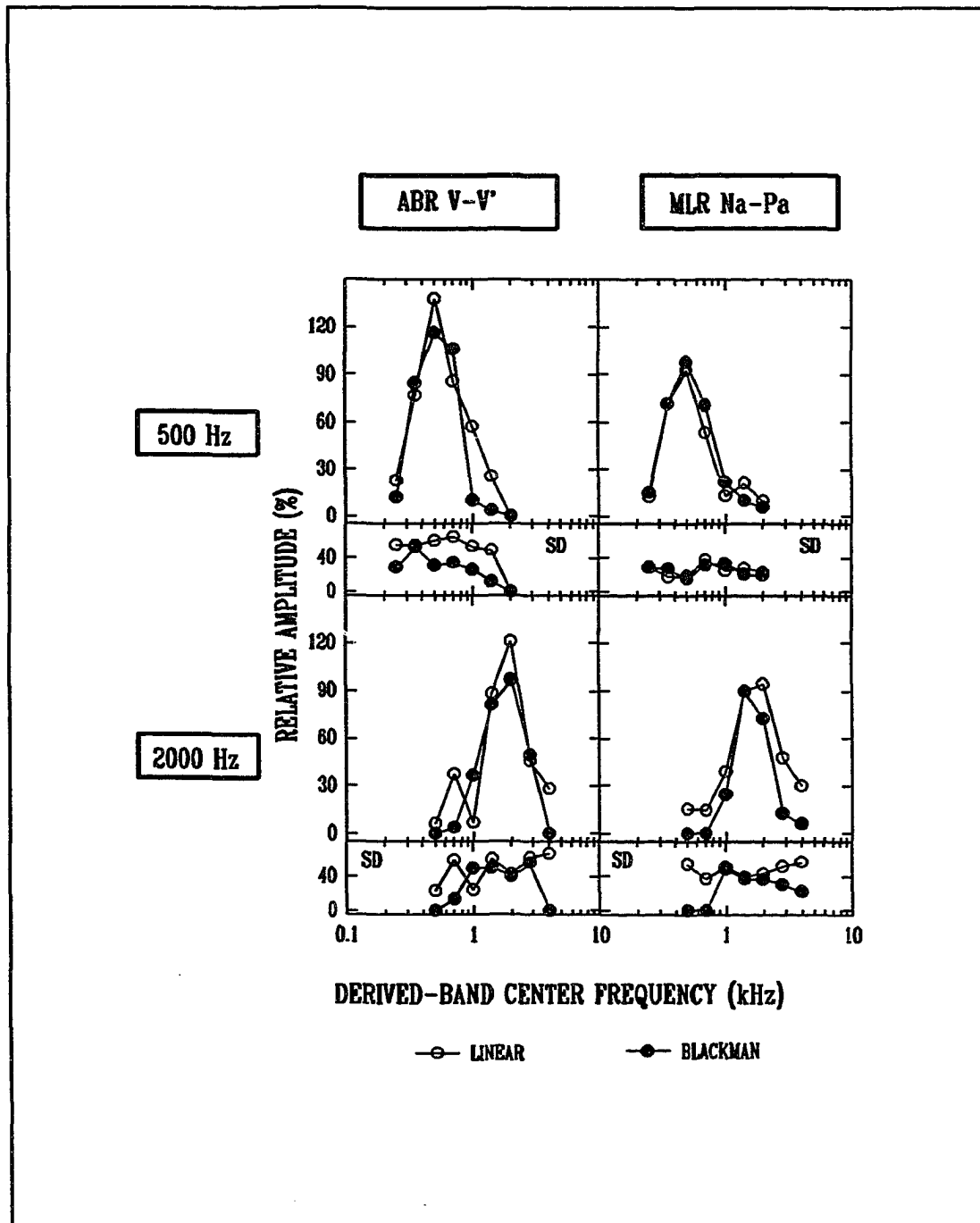


Figure 8. Mean one-octave-wide derived band response amplitude profiles and standard deviations (SD) for ABR wave V-V' and MLR wave Na-Pa to 80 dB ppe SPL 500- and 2000-Hz exact-Blackman- versus linear-gated tones.

Table 5. Results of 3-way Repeated Measures Analyses of Variance for Full-Octave Derived Responses

500 Hz							2000 Hz					
Source of Variance	df	G-G Epsilon Corrections ¹	Sums of Squares	Mean Squares	F	p ²	df	G-G Epsilon Corrections	Sums of Squares	Mean Squares	F	p ²
Wave	1		12754	12754	7.58	0.019	1		1832	1832	2.02	0.183
Error Term	11						11					
Window	1		1324	1324	0.55	0.472	1		15650	15650	2.40	0.149
Error Term	11						11					
Derived Response	6		493905	82317	49.56	0.0*	6		383348	63891	29.79	0.0*
Frequency	66	0.4769					66	0.517				
Error Term	66						66					
Wave x Window	1		3629	3629	3.39	0.93	1		1513	1513	1.12	0.312
Error Term	11						11					
Wave X DR Freq	6		18258	3043	3.25	0.025	6		13638	2273	2.52	0.076
Error Term	66	0.5954					66	0.499				
Window x DR Freq	6		11870	1978	1.79	0.151	6		10835	1805	0.88	0.456
Error Term	66	0.6391					66	0.4772				
Wave x Window x DR Freq	6		9082	1514	1.79	0.141	6		10262	1710	1.67	0.183
Error Term	66	0.7283					66	0.5855				

¹ Greenhouse-Geisser (G-G) epsilon corrections for degrees of freedom for repeated measures

² Probabilities after G-G epsilon corrections

* p < .01

Mean summary statistics (i.e., center frequency, bandwidth at 50%) were calculated for the individual subject's one-octave-wide derived response amplitude profiles, and are displayed in Table 6. The center frequencies (Hz) are located slightly above the nominal stimulus frequency for the 500-Hz tones and just below the nominal stimulus frequency for the 2000-Hz stimuli. There are only minimal differences in the center frequencies for ABR versus MLR and for the responses to exact-Blackman- versus linear-gated tones. The bandwidths (in linear Hz) for the responses to the 2000-Hz stimuli are considerably wider than for the responses to the 500-Hz tones.

Two-way repeated-measures ANOVAs (i.e., wave x window) were calculated separately for the 500- and 2000-Hz summary statistics. The results of the ANOVAs for center frequency (Hz), calculated on all 12 subjects' data, reveal no significant differences for ABR versus MLR to 500-Hz [$F(1,11)=0.02$, $p=.896$] or 2000-Hz [$F(1,11)=0.17$, $p=.687$] stimuli, and no significant differences for exact-Blackman- versus linear-gated 500-Hz [$F(1,11)=0.13$, $p=.724$] or 2000-Hz [$F(1,11)=0.04$, $p=.837$] tones. The wave x window interaction does not reach statistical significance at either stimulus frequency [500 Hz: $F(1,11)=0.59$, $p=.459$; 2000 Hz: $F(1,11)=0.14$; $p=.712$]. The two-way repeated measures ANOVAs for bandwidth (Hz) were calculated on all 12 subjects' data for 500 Hz and only 11 subjects' data for 2000 Hz (one subject's amplitude profile for MLR wave Na-Pa to the exact-Blackman-gated tone did not reach a relative amplitude of 50 percent). The results of the bandwidth ANOVAs reveal no significant differences for ABR versus MLR for 500-Hz [$F(1,11)=1.84$, $p=.203$] or 2000-Hz [$F(1,10)=2.22$, $p=.167$] tones, and no significant differences for responses to exact-Blackman- versus linear-gated tones at 500 Hz [$F(1,11)=0.87$, $p=.37$] or 2000 Hz [$F(1,10)=1.41$, $p=.262$]. The wave x window interaction does not reach statistical significance for

the 500- or 2000-Hz tonal stimuli [500 Hz: $F(1,11)=2.51$, $p=.141$; 2000 Hz: $F(1,10)=0.25$, $p=.631$]. Collectively, the results of the summary statistics show no significant differences in the frequency specificity of the ABR versus MLR, or in frequency specificity of these responses to exact-Blackman- versus linear-gated tones.

The summary statistics between the two stimulus frequencies can be compared after log transformation. The summary statistics were compared by: (1) converting the bandwidth (Hz) of each subject's 500- and 2000-Hz amplitude profiles into a common logarithm, and (2) subtracting the logarithm of the stimulus frequency from the logarithm of the center frequency. Results for 500- versus 2000-Hz summary statistics, displayed in the lower section of Table 6, show that the center frequency (in $\log_{10}$ Hz) is located either close to or slightly above the nominal stimulus for the responses to the 500-Hz tones and just below the nominal stimulus frequency for the responses to the 2000-Hz tones. There are small nonsignificant differences in $\log_{10}$ bandwidth between the nominal stimulus frequencies or between the stimulus envelopes (see Table 6).

The results of a three-way repeated measures ANOVA (stimulus frequency x wave x window) for center frequency minus stimulus frequency (in $\log_{10}$ Hz), calculated on all 12 subjects' data, reveals a significant main effect for stimulus frequency [$F(1,11)=39.82$, $p=.0001$], indicating that the responses to the 500- and 2000-Hz tones differed in the direction and degree of difference the mean center frequency of the amplitude profiles were from the nominal stimulus frequencies. The center frequencies are located slightly above the nominal stimulus frequency for the responses to the 500-Hz stimuli and slightly below the nominal stimulus frequency for the responses to the 2000-Hz tones. No significant main effects are seen for ABR versus MLR

[$F(1,11)=0.06$, $p=.80$], or for responses to exact-Blackman- versus linear-gated tones [$F(1,11)=0.13$, $p=.726$], and there are no significant interactions [frequency x wave: $F(1,11)=0.21$, $p=.655$; frequency x window: $F(1,11)=0.0$, $p=.974$; wave x window: $F(1,11)=0.82$, $p=.386$; frequency x wave x window: $F(1,11)=0.14$, $p=.713$]. A similar three-way repeated measures ANOVA for $\log_{10}$ bandwidth, conducted on 11 subjects' data, reveals no significant differences between 500- versus 2000-Hz tones [$F(1,10)=3.05$, $p=.111$], ABR versus MLR [$F(1,10)=6.09$, $p=.033$], exact-Blackman- versus linear-gated tones [$F(1,10)=2.15$, $p=.174$], and no significant interactions [frequency x wave: $F(1,10)=0.40$, $p=.543$; frequency x window: $F(1,10)=0.40$, $p=.541$; wave x window: $F(1,10)=0.01$, $p=.921$; frequency x wave x window: $F(1,10)=3.4$, $p=.095$]. To summarize, the summary statistics indicate that: (1) there are no significant differences in the frequency specificity of these evoked potentials to moderately intense 500- versus 2000-Hz brief tones; (2) the ABR and MLR to 80 dB ppe SPL brief tones are equally frequency specific; and (3) the frequency specificity of these evoked potentials is similar for the responses to the exact-Blackman- versus linear-gated tones.

D. Half-Octave Derived Responses

Grand mean derived responses representing half-octave-wide derived bands for both stimulus frequencies are shown in Figure 9. The maximum amplitudes for waves V and Pa to the 500-Hz stimuli occur in the 500-Hz derived band, with the 707-Hz derived band also containing ABRs and MLRs to both the exact-Blackman- and linear-gated stimuli. For the 2000-Hz stimuli, the largest amplitudes for waves V and Pa are seen in the 2000-Hz derived band. Cochlear contributions to wave Pa are also present in the derived bands a half octave above and below 2000 Hz. Either very small or absent peaks in response to either stimulus frequency are seen

Table 6. Mean Summary Statistics for One-Octave-Wide Derived Responses to 500- and 2000-Hz exact-Blackman- and Linear-Gated Tones.								
	500 Hz				2000 Hz			
	<u>ABR V</u>		<u>MLR Pa</u>		<u>ABR V</u>		<u>MLR Pa</u>	
	Linear ¹	Blk ²	Linear	Blk	Linear	Blk	Linear	Blk
Center Frequency (Hz)	564	537	551	556	1759	1723	1701	1703
SD	94	65	103	66	279	262	277	280
N	12	12	12	12	12	12	12	12
Bandwidth (Hz)	809	648	615	632	2174	1726	2101	1355
SD	413	182	206	123	1296	525	1313	360
N	12	12	12	12	12	12	12	11
Center Frequency minus Stimulus Frequency (Log ₁₀ Hz)	0.05	0.03	0.04	0.04	-0.06	-0.07	-0.08	-0.07
SD	0.08	0.05	0.09	0.05	0.07	0.07	0.07	0.07
N	12	12	12	12	12	12	12	12
Bandwidth (Log ₁₀ Hz)	0.55	0.49	0.45	0.47	0.49	0.42	0.48	0.35
SD	0.20	0.10	0.10	0.08	0.24	0.09	0.27	0.09
N	12	12	12	12	12	12	12	11

¹ Linear-gated tone

² exact-Blackman-gated tone

N = number of subjects

in the other derived bands. The grand mean waveforms for the half-octave derived responses are smaller in amplitude than those for the full-octave responses. The decrease in amplitude is due to the responses originating from a smaller portion of the basilar membrane (i.e., a half-octave-wide area versus a full-octave-wide area) as well as possible central masking effects. The residual electrical noise in the waveforms, however, is approximately the same in the half- and full-octave derived responses. The signal-to-noise ratio of the derived responses with the half-octave wide bands is therefore lower than those with full-octave wide bands.

Mean (and standard deviation) amplitude profiles for the 12 subjects' half-octave-wide derived responses are shown in Figure 10. The 500- and 707-Hz derived bands contribute equally to wave V-V' for the exact-Blackman- and linear-gated 500-Hz stimuli. For MLR Na-Pa, the largest amplitude occurs in the 500-Hz derived band for both of the 500-Hz tones, with significant cochlear contributions also coming from the 707-Hz band. The largest peak in the amplitude profiles for both of the 2000-Hz stimuli occurs in the 2000-Hz derived band for wave V-V'. The maximum amplitude for MLR Na-Pa occurs at 2000 Hz for the linear tone and 1410 and 2000 Hz for the exact-Blackman tone. The maximum peak in the individual subjects' ABR and MLR amplitude profiles for the 500- and 2000-Hz tones occurred within a half-octave of the nominal stimulus frequencies for at least seven out of 12 subjects. These half-octave derived response amplitude profiles show even better frequency specificity for these evoked potentials than indicated by the full-octave profiles.

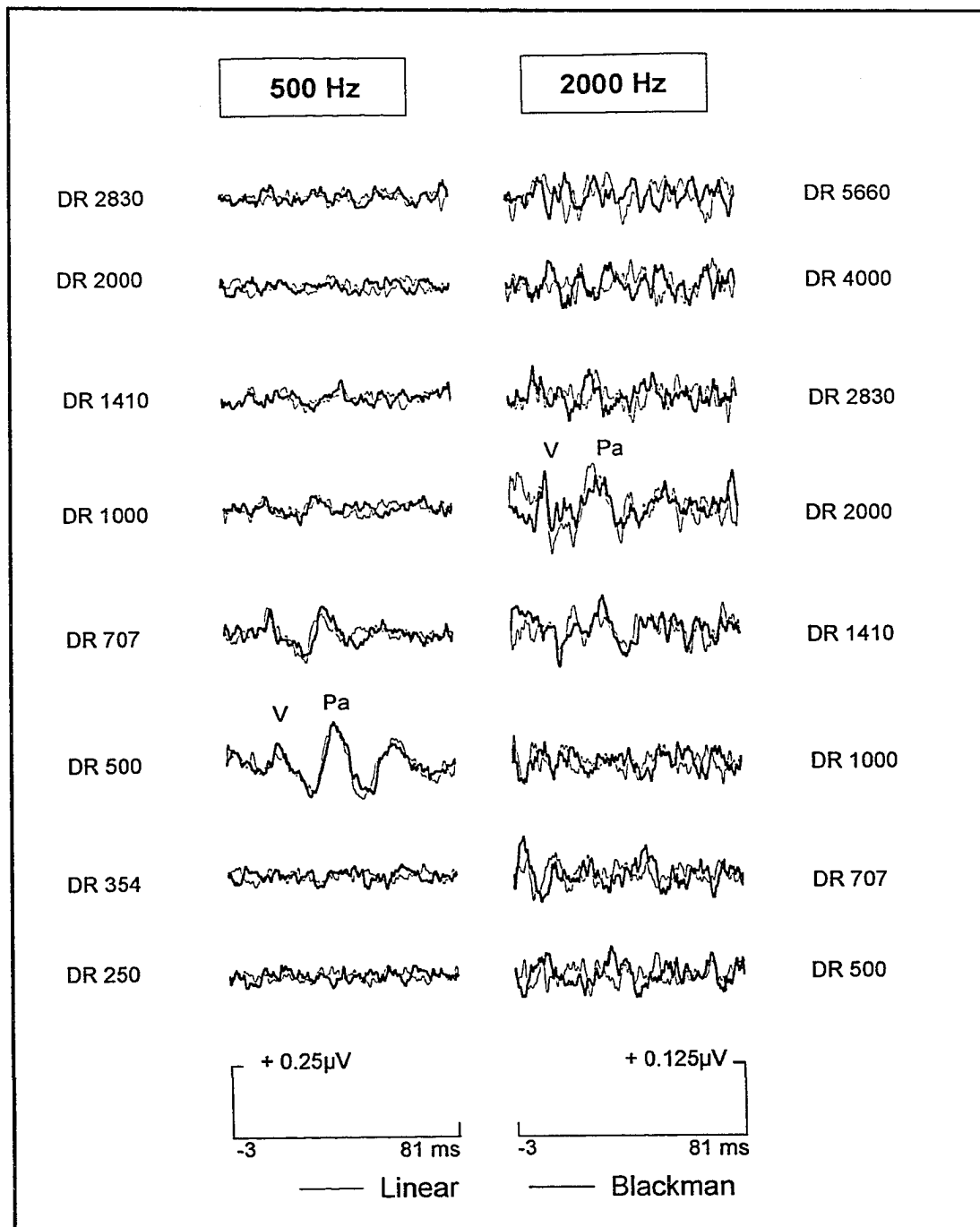


Figure 9. Grand mean (N=12) half-octave derived response waveforms to 80 dB ppe SPL exact-Blackman- and linear-gated 500- and 2000-Hz tones. Amplitude scale is +0.25 µV for the responses to the 500-Hz tones (left) and +0.125 µV for the responses to the 2000-Hz tones.

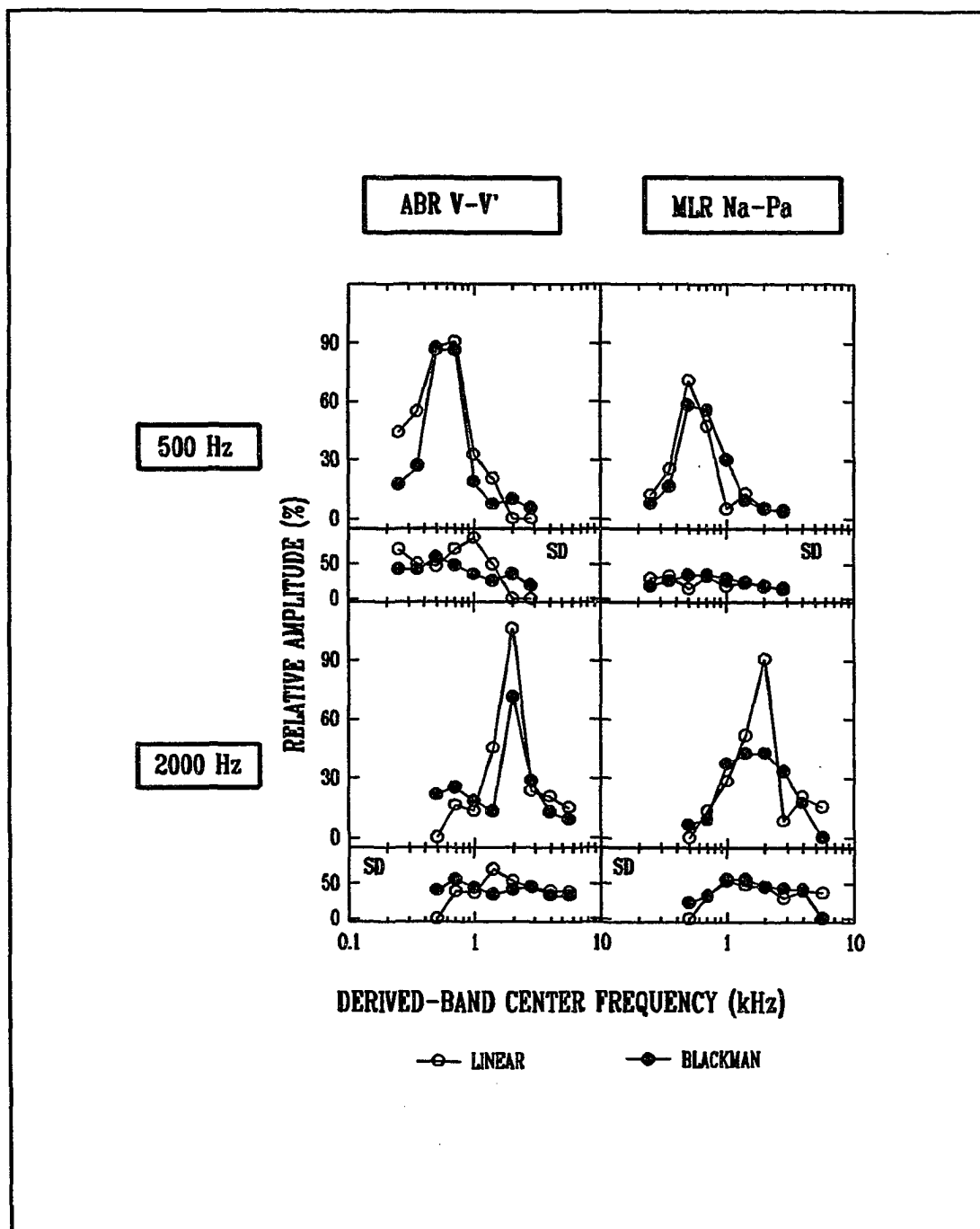


Figure 10. Mean half-octave-wide derived band response amplitude profiles and standard deviations (SD) for ABR wave V-V' and MLR wave Na-Pa to 80 dB ppe SPL 500- and 2000-Hz exact-Blackman- versus linear-gated tones.

Three-way repeated measures ANOVAs were calculated separately for the 500- and 2000-Hz half-octave derived responses. The results of these ANOVAs, displayed in Table 7, reveal an expected significant main effect for derived response center frequency for both stimulus frequencies. For the 500-Hz stimuli, the relative amplitude of ABR V-V' is significantly larger compared to MLR Na-Pa. There is no significant wave x derived band interaction, however, indicating that the ABR and MLR are equally frequency specific. The small differences in the relative amplitude between waves V-V' and Na-Pa to the 2000-Hz tones do not reach statistical significance. There are no significant differences in the response amplitude profiles for exact-Blackman- versus linear-gated tones to either the 500- or 2000-Hz tones, nor any significant interactions. The results of both the full- and half-octave derived response amplitude profiles indicate ABRs and MLRs to moderately intense 500- and 2000-Hz tonal stimuli receive cochlear contributions from a narrow region along the basilar membrane which is within one half to one octave of the nominal stimulus frequency. In addition, these profiles indicate that no significant differences exist in the frequency specificity of the ABR versus MLR or in the frequency specificity of these responses to exact-Blackman- versus linear-gated tones.

Mean summary statistics for the half-octave-wide derived response amplitude profiles for the 500- and 2000-Hz stimuli are displayed in Table 8. The center frequencies for ABR wave V and MLR wave Pa for both the 500- and 2000-Hz stimuli are located close to the nominal stimulus frequencies. Two-way repeated measures ANOVAs (i.e., wave x window) were independently calculated on the 500- and 2000-Hz half-octave summary statistics. The results of the ANOVA for center frequency (Hz), calculated on 10 subjects' data for 500 Hz and 11 subjects' data for

Table 7. Results of 3-way Repeated Measures Analyses of Variance for Half-Octave Derived Responses											
500 Hz						2000 Hz					
Source of Variance	df	G-G Epsilon Corrections ¹	Sums of Squares	Mean Squares	F	P ²	df	G-G Epsilon Corrections	Sums of Squares	Mean Squares	P ²
Wave	1		18055	18055	12.65	0.004*	1		238.30	238.30	0.23
Error Term	11						11				0.639
Window	1		1657	1657	0.95	0.349	1		2396	2396	0.87
Error Term	11						11				0.37
Derived Response	7		263521	37645	21.3	0.0*	7		173279	24754	11.38
Error Term	77	0.5121					77	0.5492			0.0*
Wave x Window	1		2108	2108	2.17	0.168	1		0.22	0.22	0.0
Error Term	11						11				0.991
Wave X DR Freq	7		15301	2186	1.92	0.146	7		15287	2184	1.7
Error Term	77	0.425					77	0.5673			0.168
Window x DR Freq	7		7443	1063	0.55	0.685	7		30729	4389	2.1
Error Term	77	0.5309					77	0.6292			0.089
Wave x Window x DR Freq	7		6397	913.96	0.89	0.461	7		4951	707.38	0.58
Error Term	77	0.4645					77	0.6343			0.694

¹ Greenhouse-Geiser (G-G) epsilon corrections for degrees of freedom for repeated measures² Probabilities after G-G epsilon corrections

* p < .01

2000 Hz, reveal no significant main effect for wave to the 500-Hz [$F(1,9)=0.07$, $p=.798$] or 2000-Hz [$F(1,10)=0.18$, $p=0.684$] tones, nor any significant effects for window to either the 500-Hz [$F(1,9)=0.77$, $p=.403$] or 2000-Hz [$F(1,10)=0.50$, $p=.496$] stimuli. The wave x window interaction does not reach statistical significance for either stimulus frequency [500 Hz: $F(1,9)=0.04$, $p=.841$; 2000 Hz: $F(1,10)=0.11$, $p=.745$]. A similar two-way repeated measures ANOVA for bandwidth (Hz), calculated on nine and seven subjects' data for 500- and 2000-Hz tones respectively, shows no significant differences between: ABR versus MLR to the 500-Hz [$F(1,8)=3.94$, $p=.082$] or 2000-Hz [$F(1,6)=1.61$, $p=.251$] tones; or exact-Blackman- versus linear-gated tones at 500 Hz [$F(1,8)=0.07$, $p=.802$] and 2000 Hz [$F(1,6)=4.53$, $p=.078$]. No significant wave x window interaction is seen for either of the summary statistics measures for the 500- or 2000-Hz tones [500 Hz: $F(1,8)=0.02$, $p=.882$; 2000 Hz: $F(1,6)=0.26$, $p=.632$]. Repeated measures ANOVAs comparing 500- and 2000-Hz bandwidth measures could not be calculated for the half-octave profiles because only a few subjects (5/12) had complete results at both frequencies.

E. Full- and Half-Octave Derived Response Latencies

Individual subjects' derived response latencies were examined in order to determine whether the latency differences reported for the nonmasked responses to the exact-Blackman- versus linear-gated tones were due to differences in "place" of cochlear excitation or to differences in the stimulus rise times (i.e., 2.0 cycles for the linear-gated tones versus 2.5 cycles for the exact-Blackman-gated tones). ABR wave V and MLR wave Pa derived response latencies for the 500- and 2000-Hz tones were measured from both the one-octave-wide and half-octave-

Table 8. Mean Summary Statistics for Half-Octave-Wide Derived Responses to 500- and 2000-Hz exact-Blackman- and Linear-Gated Tones.								
	500 Hz				2000 Hz			
	<u>ABR V</u>		<u>MLR Pa</u>		<u>ABR V</u>		<u>MLR Pa</u>	
	Linear ¹	Blk ²	Linear	Blk	Linear	Blk	Linear	Blk
Center Frequency (Hz)	572	609	576	657	2081	1923	2199	1922
SD	176	117	125	136	686	729	1215	549
N	11	11	12	12	12	11	12	12
Bandwidth (Hz)	622	602	401	460	2058	1545	2020	1311
SD	244	438	189	144	1122	957	1187	640
N	11	11	11	9	11	9	10	11
Center Frequency minus Stimulus Frequency (Log ₁₀ Hz)	0.04	0.08	0.05	0.11	0.00	-0.06	0.00	-0.03
SD	0.13	0.09	0.09	0.09	0.14	0.21	0.19	0.13
N	11	11	12	12	12	11	12	12
Bandwidth (Log ₁₀ Hz)	0.45	0.40	0.29	0.31	0.41	0.36	0.40	0.30
SD	0.13	0.20	0.10	0.07	0.14	0.20	0.17	0.16
N	11	11	11	9	11	9	10	11

¹ Linear-gated tone

² exact-Blackman-gated tone

N = number of subjects

bands corresponding to the nominal stimulus frequencies. Mean latencies for the derived bands representing one-octave-wide regions along the basilar membrane are displayed in the top section of Table 9. A three-way repeated measures ANOVA (i.e., stimulus frequency x wave x window) was calculated on 11 subjects' full-octave derived response latencies (one subject, who had responses in the 1410-Hz derived band, did not have an ABR or MLR to the 2000-Hz exact-Blackman-gated tone in the 2000-Hz derived band). The results of the ANOVA reveal expected significant main effects for stimulus frequency [$F(1,10)=342.50$, $p < .001$] and wave [$F(1,10)=3589.27$, $p < .001$], with longer latencies for the responses to the 500-Hz tones and for MLR wave Pa. There is also a significant main effect for exact-Blackman- versus linear-gated tones [$F(1,10)=17.03$, $p=.002$], with the responses to the exact-Blackman-gated tones having a longer latency. No interactions reach statistical significance [frequency x wave: $F(1,10)=7.27$, $p=.023$; frequency x window: $F(1,10)=4.47$, $p=.061$; wave x window: $F(1,10)=0.58$, $p=.462$; frequency x wave x window: $F(1,10)=3.01$, $p=.113$].

Mean half-octave-wide derived response latencies for ABR wave V and MLR wave Pa to the 500- and 2000-Hz exact-Blackman- and linear-gated tones are displayed in the lower section of Table 9. The latencies of the responses to both stimulus envelopes are longer for the half-octave-wide derived responses at each of the nominal stimulus frequencies compared to the full-octave-wide derived responses. These latency differences between the full- versus half-octave derived bands, however, were not evaluated statistically. Two-way repeated measure ANOVAs (wave x window) were calculated independently for the responses to 500- versus 2000-Hz tones. The analyses were calculated on nine subjects' data for the 500-Hz tones and eight subjects' data for 2000-Hz tones (the remainder of the subjects did not show ABRs and/or MLRs in

the half-octave-wide derived responses for the nominal frequencies of the stimuli). An expected main effect for wave is seen for the responses to the 500-Hz tones [$F(1,8)=3551.72$, $p < .001$] and to the 2000-Hz tones [$F(1,7)=1437.33$, $p < .001$], with longer latencies for MLR wave Pa. A significant main effect is also seen for window for the responses recorded to the 500-Hz tones [$F(1,8)=16.03$, $p = .004$] with the responses to the exact-Blackman-gated tones having a longer latency compared to responses to the linear-gated tones. Although not statistically significant, there was a trend for the responses to the 2000-Hz exact-Blackman-gated tones to be slightly longer than the responses to the linear-gated tones [$F(1,7)=11.98$, $p = .011$]. The wave x window interaction does not reach statistical significance for either the 500- or 2000-Hz tones [500 Hz: $F(1,8)=0.15$, $p=.713$; 2000 Hz: $F(1,7)=3.41$, $p=.107$]. These derived-response latency measures were not compared across stimulus frequency due to the limited number of subjects' data available for this comparison.

The derived response results demonstrate that, when "place" of basilar membrane excitation is held constant, significant latency differences remain between the responses to the exact-Blackman- versus linear-gated tones. This suggests that the latency effect is not due to differences in the frequency or place specificity of the responses. Rather it is due to the rise time differences between the stimuli. As such, the latency effect would be more pronounced for the lower versus higher frequency tonal stimuli.

Table 9. Mean ABR wave V and MLR wave Pa latencies (ms) for full-octave (top) and half-octave (bottom) derived responses to 80 dB ppe SPL 500- and 2000-Hz exact-Blackman- versus linear-gated tones.

	500 Hz Tones				2000 Hz Tones			
	500 Hz Derived Response				2000 Hz Derived Response			
	<u>Wave V</u>		<u>Wave Pa</u>		<u>Wave V</u>		<u>Wave Pa</u>	
	Linear ¹	Blk ²	Linear	Blk	Linear	Blk	Linear	Blk
Full-Octave								
DR Latencies	12.33	13.06	33.26	34.94	8.02	8.64	28.01	28.43
SD	0.82	0.80	1.83	1.24	0.82	0.59	1.58	1.57
N	12	12	12	12	12	11	12	11
Half-Octave								
DR Latencies	13.46	14.18	34.76	35.37	8.36	8.81	27.75	28.46
SD	1.53	0.48	1.22	1.12	0.53	0.39	1.57	1.40
N	10	10	12	11	12	10	11	8

¹ Linear-gated tone

² exact-Blackman-gated tone

N = number of subjects

III. DISCUSSION

A. Frequency specificity of evoked potentials to brief tones

The mean derived response (full- and half-octave) amplitude profiles demonstrate that ABR wave V-V' and MLR wave Na-Pa to 80 dB ppe SPL brief tones show good frequency specificity, as indicated by maxima in the amplitude profiles occurring either at the nominal stimulus frequency or within a narrow range (i.e., one half octave) of this frequency. The ABR and MLR amplitude profiles show a sharp dropoff in the amplitudes of the responses on the low- and high-frequency sides of the profile peak, indicating little or no cochlear contributions to these evoked potentials from regions of the basilar membrane one or more octaves away from the probe frequency. The center frequency values calculated on these amplitude profiles also indicate that ABRs and MLRs to these moderately intense 500- and 2000-Hz tonal stimuli show good frequency specificity. The mean center frequencies of the full- and half-octave amplitude profiles for waves V-V' and Na-Pa approximated the actual stimulus frequencies.

Direct comparison of these bandwidth measures to previous studies is difficult due to differences in stimulus frequencies, stimulus intensities, and/or masking techniques employed. However, the bandwidth measures reported in the present study are close to but slightly wider than the "W50" measures reported by Stapells and colleagues (Mackersie *et al.*, 1993; Wu and Stapells, 1994) for waves V-V' and Na-Pa to 60 dB ppe SPL 500- and 2000-Hz tones presented in the presence of 70-80 dB SPL pure-tone maskers. In addition, the bandwidth values we report for the full- and half-octave derived response ABR amplitude profiles for the 2000-Hz linear-gated stimuli (i.e., means of 2174 Hz and 2058 Hz, respectively) are close to the 1850 Hz "W50" value which can be

extrapolated from derived-response compound action potential (CAP) amplitude profiles presented by Eggermont (1976, figure 22a). Consistent with this, several studies in animals have shown that the tuning characteristics of the CAP and wave V are similar (e.g., Brown and Abbas, 1987; Dolan, Mills and Schmeidt, 1985; Mitchell and Fowler, 1980). Comparison of the bandwidths reported in the current study to Q10 values of frequency tuning curves (FTCs) reported in the literature (e.g., Evans, 1975) are not possible because: (1) the present values were calculated at a relative amplitude of 50% rather than at 10 dB above the tip of the FTC; and (2) the reported Q10 values were measured at threshold levels whereas the present values were calculated at suprathreshold levels.

The HP noise results of this study also indicate that the ABR/MLR show equally good place specificity to 500- and 2000-Hz tones (presented at 80 dB ppe SPL). HP noise masking prevents contributions to these responses from areas of the basilar membrane above the cutoff frequency of the noise and can therefore be used to investigate the regions of the cochlea that are contributing to the nonmasked ABRs and MLRs to tonal stimuli. The amplitude profiles for the HP masking conditions illustrate that there are no significant decreases in response amplitudes until the cutoff frequency of the noise is lowered to 707 Hz for the 500-Hz stimuli, and to 2000 Hz for the 2000-Hz tones. This indicates that any spread of stimulus energy or cochlear excitation to frequency regions more than one-half to one octave above the nominal frequency does not contribute to these responses. Similarly, significant increases in the response latencies to the 500-Hz tones occurred only when the cutoff frequency of the HP noise was within a half to one octave of the nominal stimulus frequency. Lowering of the cutoff frequency of the noise from 8000 to 2830 Hz produced small but nonsignificant increases in latencies

to the 2000-Hz tones. Significant latency changes for the responses to 2000-Hz tones are less likely compared to the responses to the 500-Hz tones because: (1) removing contributions to the response from more basal regions of the cochlea produce very small changes in the response latencies to the 2000-Hz tones due to the better neural synchrony of the higher frequency regions of the cochlea (Kiang, 1975); (2) an equivalent latency shift corresponds to a greater distance along the basilar membrane in the 2000-Hz region compared to the 500-Hz region (Tonndorf, 1970); and (3) the velocity of the travelling wave is greater for the basal versus apical regions of the cochlea (Békésy, 1960). When the cutoff frequency of the noise was equal to or lower than the nominal stimulus frequency, the evoked potentials completely disappear, demonstrating that cochlear contributions to these responses come from a relatively narrow region along the cochlear partition. The changes in the amplitudes and latencies of the responses as a function of the cutoff frequency of the HP noise confirm the frequency and place specificity of the ABR/MLR to 80 dB ppe SPL nonmasked 500- and 2000-Hz brief tones.

The results of the present study are in agreement with previous studies which have investigated, in normal-hearing adults, the frequency specificity of the ABR to moderately-intense nonmasked tonal stimuli (Burkard and Hecox, 1983; Folsom, 1984; Klein, 1983; Jacobson, 1983; Mackersie et al., 1993; Picton et al., 1979; Stapells, 1984; Stapells and Picton, 1981; Wu and Stapells, 1994). Employing a pure-tone masking paradigm, Klein demonstrated that the slow-wave component of the ABR to 77 dB ppe SPL 500- and 1000-Hz tones are best tuned to narrow cochlear regions surrounding the nominal stimulus frequency (e.g., for the 500-Hz tone, the tip of the tuning curve occurred at 500-600 Hz), illustrating that the response has a good degree of frequency specificity. Later

pure-tone masking studies by Folsom (1984) and by Stapells and colleagues (Mackersie et al., 1993; Wu and Stapells, 1994) also report that ABRs to 60-75 dB ppe SPL tonal stimuli show masking profiles which are narrow and centered on the nominal stimulus frequency. When these same stimuli are presented at a higher stimulus intensity (e.g., 95 dB ppe SPL), however, there is a spread of excitation to the higher frequency regions of the cochlea which results in a decrease in the frequency specificity of the response (Folsom, 1984).

Studies which have investigated the frequency specificity of the ABR to tonal stimuli by comparing the responses recorded in quiet to those recorded in notched noise have shown that, at stimulus intensities greater than 70 dB ppe SPL, the response is in part influenced by contributions from frequencies away from the nominal stimulus frequency (Beattie and Kennedy, 1992; Jacobson, 1983; Picton et al., 1979; Stapells, 1984; Stapells and Picton, 1981). Notched noise masking significantly increases the latency and decreases the amplitude of ABR wave V compared to the nonmasked response, with larger changes in wave V latency occurring for the responses to the 500-Hz tones compared to the responses to the 2000-Hz tones. The results of the present study demonstrate that wave V latency for nonmasked 80 dB ppe SPL 500-Hz tones is, in part, mediated by cochlear contributions from the 707 and 1000 Hz regions of the basilar membrane.

The disadvantage of the notched-noise technique for investigation of the frequency specificity of the ABR or MLR, however, is that there is spread of masking into the notch from the low-frequency edge of the notch. Picton and coworkers reported that, using noise filters with slopes of 48 dB/octave, the effective depth of the notch was reduced to approximately 27 dB by the spread of masking from the low-frequency edge (Picton et al., 1979). The spread of the masking is greater at higher

intensities (Egan and Hake, 1950; Ehmer, 1959a,b), and this upward spread of masking may be more pronounced in individuals with sensorineural hearing loss (Eggermont, 1977; Trees and Turner, 1986). In contrast to notched noise masking, the HP/DR technique utilizes only HP noise. There is therefore little or no upward spread of masking. As a consequence, the HP/DR technique yields a more frequency- and place-specific evaluation of the ABR and MLR (Stapells et al., 1994, 1985).

The present study's findings on the frequency specificity of the MLR are in agreement with those of Mackersie et al. (1993) and Wu and Stapells (1994). All three studies show that the largest cochlear contributions to MLR wave Na-Pa come from regions of the basilar membrane corresponding to the stimulus probe frequencies and thus exhibit good frequency specificity. The derived response amplitude profiles in the present study also show significant contributions to the MLR to the 500-Hz tones from the 354- and 707-Hz cochlear regions and from the 1410- and 2830-Hz regions for the MLR to the 2000-Hz tonal stimuli. Cochlear contributions to MLRs from a slightly wider region along the basilar membrane for 80 (present study) versus 60 (Mackersie et al., 1993; Wu and Stapells, 1994) dB ppe SPL tones is not surprising in view of the increased spread of cochlear excitation that occurs with higher stimulus intensities (e.g., Anderson, Rose, Hind and Brugge, 1970; Kiang, Sachs, and Peake, 1967; Rose, Hind, Anderson, and Brugge, 1971), as well as the effects of increased spectral splatter.

B. Frequency Specificity of the ABR versus the MLR

No significant differences were found in the frequency specificity of ABR wave V-V' versus that of MLR wave Na-Pa. This was illustrated by the full- and half-octave- wide derived response amplitude profiles, the summary statistics calculated on these profiles, as well as the

amplitude and latency profiles for the HP noise conditions. The lack of significance for the differences in frequency specificity of the ABR versus MLR is in agreement with studies by Mackersie *et al.* (1993) and Wu and Stapells (1994), which demonstrated that the ABR and MLR are equally frequency specific for low-intensity (i.e., 60 dB ppe SPL) 500- and 2000-Hz tones. The results of the present study, however, are not in agreement with those of Smith *et al.* (1990), who concluded that the MLR is less frequency specific compared to the ABR because their MLR frequency tuning curves had a similar V-shape but wider width than the ABR curves and that the MLRs were more susceptible to effects of pure-tone masking than the ABR. The contradictory findings between Smith *et al.* (1990) and the present results may be due to differences in the masking procedures employed (HP noise versus pure-tone masking), differences in generators between the species (humans versus gerbils), or differences in adaptation characteristics for the ABR versus the MLR.

C. Frequency specificity of responses to 500- versus 2000-Hz tones

Summary statistics calculated on the derived response amplitude profiles demonstrate that the evoked potentials to 500- versus 2000-Hz brief tones are equally frequency specific. Comparisons of the mean bandwidths (in $\log_{10}$ Hz) between the nominal stimulus frequencies reveal only small nonsignificant differences in these values. A significant main effect for stimulus frequency was seen when the common logarithm of the stimulus frequency was subtracted from the common logarithm of the center frequency, however, indicating that responses to the 500- versus 2000-Hz brief tones differ in the direction that the mean center frequency of the amplitude profiles is from the nominal stimulus frequency. The center frequencies of the ABR and MLR amplitude profiles are located either close to or slightly above the nominal stimulus

frequency for the 500-Hz tones and just below the nominal stimulus frequencies for the 2000-Hz tones. The present findings of no difference in the frequency specificity of the ABR/MLR to 500- versus 2000-Hz tonal stimuli agrees well with several studies, showing similar correlations at 500 and 2000 Hz for comparisons between tone-evoked ABRs and pure-tone behavioral thresholds for normal and hearing-impaired subjects (Munnerley et al., 1991; Stapells et al., 1995; 1990).

When bandwidths of the amplitude profiles are compared using a linear frequency scale, the "W50" values for the 2000-Hz stimuli are approximately three to four times wider than the 500-Hz amplitude profiles. This finding is in general agreement with psychoacoustical studies by Greenwood (1961), Hawkins and Stevens (1950), and Scharf (1970), which demonstrate that the critical bandwidth varies as a function of frequency. Specifically, these studies have shown that estimates of the critical bandwidth (Hz) are approximately three times wider when a 2000-Hz pure tone is located at the center of the passband of the noise compared to when a 500-Hz tone is at the center of the passband. Comparisons of the summary statistics between nominal stimulus frequencies are best made on a logarithmic frequency basis, however, as it more accurately reflects how frequency is represented on the basilar membrane (e.g., Tonndorf, 1970).

D. Responses to exact-Blackman- versus linear-gated tones

The nonmasked absolute latencies of ABR wave V and MLR wave Pa are significantly longer in response to the exact-Blackman-gated tones compared to the linear-gated tones at either stimulus frequency. The latency differences between the stimulus envelopes are more pronounced for the 500- versus 2000-Hz tones. Significant latency differences between the exact-Blackman- versus linear-gated tones are also present

in the full-octave-wide derived responses from cochlear regions corresponding to the nominal stimulus frequencies. Because the latency differences between these stimulus envelopes exists when place of cochlear excitation is held constant, the latency differences are likely due to differences in the rise time of the stimuli (i.e., 2 cycle rise time for the linear-gated tones versus 2.5 cycle rise time for the exact-Blackman-gated tones) rather than differences in their cochlear excitation. The larger latency difference for the lower frequency stimuli may be explained by the 0.5 cycle rise time difference between the stimuli being equal to 1.0 ms at 500 Hz compared to 0.25 ms at 2000 Hz.

The derived response (full- and half-octave-wide) amplitude profiles, the summary statistics calculated on these profiles, and the mean amplitude and latency profiles for the responses recorded in HP noise, show no significant differences exist in the frequency specificity of the evoked potentials to the exact-Blackman- versus linear-gated tones. This finding is in agreement with unpublished results of Purdy and Abbas (1989), and does not provide support for the recommendation to use Blackman-gated tones specifically to improve the frequency specificity of the ABR (e.g., Gorga et al., 1992; Gorga and Thornton, 1989; Telian and Kileny, 1989). The lack of significance for the differences in the frequency specificity of the ABR and MLR to exact-Blackman- versus linear-gated tones indicates the inability of the auditory system to reflect the small temporal differences in the acoustic waveforms of the stimuli. The acoustic spectra of these brief tones may therefore not reflect their "effective" spectra. The effective spectrum of the stimuli is determined by the interaction of the characteristics of the stimuli, the transducer and the transfer characteristics of the ear canal, middle ear, and the inner ear (Fowler

and Durrant, 1994), as well as more central structures (e.g., VIIIth nerve, brainstem and cortex). Several investigators have suggested that there is an effective portion of the tone which elicits the ABR (e.g., Kodera, Marsh, Suzuki, and Suzuki, 1983; Suzuki and Horiuchi, 1981). If this is true, then the acoustic spectra, which reflect the total duration of the brief tone, may present a misleading picture of the energy as a function of frequency present in the effective portion of the tonal stimulus.

The HP/DR technique employed in the present study provides a direct measure of the physiological effective spectra of the stimuli (i.e., the frequencies in the stimuli which actually contribute to the response). The results of this study clearly show that the acoustic spectra of the exact-Blackman- and linear-gated tones (Figure 1) do not accurately reflect the effective spectra of the stimuli (at least for the energy present in the sidelobes of the tonal stimuli). The major cochlear contributions to these evoked potentials to 80 dB ppe SPL exact-Blackman- and linear-gated brief tones come from the nominal stimulus frequency or within a narrow range (i.e., about one-half octave) of this frequency. The spectral differences between these tones are also not reflected in either the ABR or MLR.

The present findings for the exact-Blackman- versus linear-gated tones apply only to moderately intense (80 dB ppe SPL) stimuli. It remains to be investigated whether there would be differences in the frequency specificity of the ABR and/or MLR to these stimuli at higher stimulus intensities. The unpublished data from the Purdy and Abbas (1989) study (which investigated responses of hearing-impaired subjects to high-intensity tones), however, do not suggest any significant

differences in the frequency specificity of the ABR to these exact-Blackman- versus linear-gated tones at stimulus intensities of 90 dB ppe SPL or greater.

E. ABRs and MLRs to 500- versus 2000-Hz tones

ABRs and MLRs recorded to 80 dB ppe SPL 500-Hz tones in quiet are longer in latency compared to the responses recorded to the same intensity 2000-Hz tones. The longer latency of the nonmasked 500-Hz responses is due to the longer travel time along the basilar membrane to reach the apical regions of the cochlea. Latency delays of approximately 3 to 4 ms are seen for waves V and Pa as stimulus frequency is decreased from 2000 to 500 Hz (Table 2). There is no significant difference in the frequency-based latency delay for the ABR versus MLR. The size of the latency shift for waves V and Pa as a function of stimulus frequency reported in this study are in agreement with the latency shifts reported by previous investigations (Stapells, 1984; Stapells and Picton, 1981; Wu and Stapells, in preparation). The longer latencies for the nonmasked responses to the 500-Hz tones may also be, in part, due to their longer rise times (4-5 ms) compared to the 2000-Hz tones (1-1.25 ms). Previous studies have shown longer rise times result in later wave V latencies (Jacobson, 1983; Koderá, Yamane, Yamada, and Suzuki, 1977; Stapells and Picton, 1981).

In the present study, no differential effects of stimulus frequency were found on the nonmasked amplitudes of waves V-V' and Na-Pa, though there was a nonsignificant trend for wave Na-Pa to be slightly larger for the responses to the 500-Hz tones compared to the 2000-Hz tones. This finding is in agreement with the results of Wu and Stapells who also report no significant wave V-V' amplitude differences for 500- versus 2000-Hz tones (Wu and Stapells, in preparation).

However, these authors did report slightly but significantly larger Na-Pa amplitudes for the 500- versus 2000-Hz tonal stimuli. The current study also showed that the nonmasked amplitude of MLR wave Na-Pa is significantly larger compared to ABR wave V-V'. This finding is in agreement with previous studies (Scherg and Volk, 1983; Wu and Stapells, 1994; Wu and Stapells, in preparation) and this amplitude effect may be, in part, a reflection of the nature of the measurement (i.e., determining where wave V ends and wave Na begins).

The evoked potentials recorded in HP noise masking are smaller in amplitude and longer in latency than the nonmasked responses (both stimulus frequencies). These changes in response amplitudes and latencies are evident at the highest HP noise cutoff frequency for each tonal stimulus (i.e., 4000 Hz for the 500-Hz tones and 8000 Hz for the 2000-Hz tones) and are probably primarily due to low-level broadband masking resulting from the input intensity of the broadband noise being higher than the stopband attenuation of the HP filter. Burkard and Hecox (1983) demonstrated that broadband masking produces a decrease in amplitude and increase in latency of ABR wave V. This low-level broadband masking effect had a greater impact on the amplitudes of the ABRs and MLRs recorded to the 2000-Hz tones compared to those recorded to the 500-Hz stimuli. This effect was especially evident for MLR wave Na-Pa. Several researchers have shown that broadband, high-pass, or notched noise masking produce greater decreases in the amplitude of wave V-V' to higher versus lower frequency stimuli (Beattie and Kennedy, 1992; Burkard and Hecox, 1983; Purdy et al., 1989; Stapells, 1984; Stapells et al., 1994, 1985). This masking effect is most likely due to larger threshold shifts produced by broadband noise for higher- versus lower-frequency tonal stimuli (Hawkins and Stevens, 1950).

An alternative, or more likely an additional factor accounting for some of the changes in the amplitude and latency with the introduction of the high-pass noise with a high-frequency cutoff may be the possibility of a central masking effect. The MLR has been shown to be more susceptible than the ABR to masking noise delivered to the ear contralateral to stimulation (Galambos and Makeig, 1992), as well as to masking delivered ipsilaterally (Gott and Hughes, 1989). This greater effect of "central masking" on the MLR would be consistent with the findings of the present study.

In the current study, the derived response waves V and Pa latencies from the full-octave-wide bands corresponding to the nominal stimulus frequencies are shorter compared to those from the half-octave-wide bands. Seen for responses to both stimulus frequencies, this latency effect was nevertheless more pronounced for the responses to the 500-Hz stimuli. These latency differences for the full- versus half-octave derived responses are probably due to the fact that the full-octave-wide band contains all of the frequencies contributing to the half-octave-wide band plus contributions from frequencies one-quarter octave above and below the edges of the half-octave band. Assuming higher frequencies determine response latency, cochlear contributions to the evoked potentials from the quarter-octave-wide region located above (i.e., basal to) the half-octave-wide band would yield shorter latencies. The latency effect between the derived bands may also be a reflection of the differences in their areas of cochlear excitation. The area of the basilar membrane, and thus the number of auditory nerve fibers, free to respond to the stimulus is greater for the full- versus half-octave-wide bands, and therefore responses from the full-octave bands would have shorter latencies (and larger amplitudes). This latency effect between the derived bands was more pronounced for the low- versus

high-frequency tonal stimuli because of: (1) the better neural synchrony of the higher frequency regions of the cochlea; (2) the speed of the travelling wave is faster in the basal versus apical regions of the cochlea; and (3) the half-octave wide differences between the full- versus half-octave derived bands correspond to larger distance along the basilar membrane for the low versus high frequency tones. The difference in mean wave V latencies for the full- and half-octave derived responses reported in this study (i.e., approximately 1.1 ms for the 500-Hz tones and 0.3 ms for the 2000-Hz tones) represents an estimate of the travelling wave delay between the 1000 to 707 Hz regions of the cochlea for the responses to the 500-Hz tones, and the 4000 to 2830 Hz regions for the responses to the 2000-Hz tones. These shifts in wave V latency as a function of change in the area of cochlear excitation are in general agreement with the wave V latency shifts of approximately 0.95 ms and 0.16 ms reported by Don and Eggermont (1978) for the same cochlear regions.

F. Implications

The results of this study demonstrate that the ABR and MLR to 80 dB ppe SPL 500- and 2000-Hz brief tones show equally good frequency and place specificity. There are no significant differences in the frequency specificity of: (1) ABR wave V-V' versus MLR wave Na-Pa; (2) the evoked potentials to 500- versus 2000-Hz tones; and (3) the evoked potentials to exact-Blackman- versus linear-gated tones. ABRs and MLRs to moderately intense nonmasked tonal stimuli may therefore be used to accurately assess both low- and high-frequency hearing sensitivity, given that appropriate technical factors are considered in recording these evoked potentials. For simultaneous recordings of the ABR and MLR, the following stimulus and recording parameters are suggested:

"2-1-2" cycle brief tones with alternating onset polarity; stimulus rates of $\leq 15/s$; 10-1000 Hz EEG analog filter settings with ≤ 12 dB/octave rolloff slopes; and post-stimulus analysis times of at least 75 ms.

The present study investigated the frequency specificity of these evoked potentials to moderately intense (i.e., 80 dB ppe SPL) brief tones. As stimulus intensity is increased above 80 dB ppe SPL, there will likely be greater contributions to the evoked potentials from frequencies outside of the nominal stimulus frequency, thus reducing the frequency specificity of the responses (Burkard and Hecox, 1983; Folsom, 1984; Picton et al., 1979; Stapells, 1984; Stapells and Picton, 1981). The poorer frequency specificity of the ABR and/or MLR to nonmasked tonal stimuli presented at high stimulus intensities can have detrimental effects in trying to estimate pure-tone behavioral thresholds in hearing-impaired subjects. In some clinical populations, ABR and/or MLR thresholds may be the only audiologic information that is available for determining the nature and degree of hearing loss present, as well as selecting appropriate amplification. Therefore, it is important for future studies to better define the frequency specificity of these evoked potentials to high-intensity tonal stimuli.

The stimulus intensities for brief tones that may be safely employed using the HP/DR technique are limited to 80 dB ppe SPL or lower. This is due to the high levels of broadband noise that are required to completely mask the evoked potentials. Higher noise intensities may cause temporary or permanent threshold shifts. There are, however, other masking techniques (such as notched noise masking) which may be used to investigate the frequency specificity of evoked potentials to higher intensity brief tones, due to the significantly lower levels of noise required (Stapells et al., 1994, 1985).

The results of the present study do not support the suggestion that the MLR provides a more frequency-specific response to 500-Hz tonal stimuli compared to the ABR. The choice of utilizing the ABR or MLR in evaluating low-frequency hearing sensitivity should therefore be based on individual subject characteristics (e.g., age) as well as the time constraints of the testing situation (faster stimulus rates may be used for ABR testing). Furthermore, the findings of this current study do not support the recommendation to use exact-Blackman-gated tones in place of conventional linear-gated signals specifically to improve the frequency specificity of the evoked potentials.

ACKNOWLEDGMENTS

This manuscript is based on the Ph.D. dissertation of the first author, submitted to the City University of New York Ph.D. Program in Speech and Hearing Sciences. The research in this project was funded in part by an American Speech-Language-Hearing Foundation Student Research grant (1993) to the first author, as well as by NIDCD grant 8P50 DC00223 to the second author.

LITERATURE CITED

- Achor, L.J., and Starr, A. (1980). Auditory brain stem responses in the cat. I. Intracranial and extracranial recordings. *Electroencephalography and Clinical Neurophysiology*, 48, 154-173.
- Alberti, P.W., Hyde, M.L., Riko, K., Corbin, H., and Fitzhardinge, P.M. (1985). Issues in early identification of hearing loss. *Laryngoscope*, 95, 373-381.
- American National Standards Institute I. (1969). American National Standard Specifications for Audiometers, S3-6.
- Anderson, D.J., Rose, J.E., Hind, J.E., and Brugge, J.F. (1970). Temporal position of discharges in single auditory nerve fibers within the cycle of a sine-wave stimulus: frequency and intensity effects. *Journal of the Acoustical Society of America*, 49, 1131-1139.
- Azzena, G.B., Conti, G., Santarelli, R., Ottaviani, F., Paludetti, G., and Maurizi, M. (1995). Generation of human auditory steady-state responses (SSRs). I: Stimulus rate effects. *Hearing Research*, 83, 1-8.
- Beattie, R.C., and Boyd, R.L. (1985). Early/middle evoked potentials to tone bursts in quiet, white noise and notched noise. *Audiology*, 24, 406-419.
- Beattie, R.C., and Kennedy, K.M. (1992). Auditory brainstem response to tone bursts in quiet, notch noise, highpass noise, and broadband noise. *Journal of the American Academy of Audiology*, 3, 349-360.

- Beattie, R.C., Moretti, M., and Warren, V. (1984). Effects of rise-fall time, frequency, and intensity on the early/middle evoked response. *Journal of Speech and Hearing Disorders*, 49, 114-127.
- Beattie, R.C., and Spence, J. (1991). Auditory brainstem response to clicks in quiet, notch noise and highpass noise. *Journal of the American Academy of Audiology*, 2, 76-90.
- Beiter, R.C., and Hogan, D.D. (1973). Effects of variations in stimulus rise-decay time upon the early components of the auditory evoked response. *Electroencephalography and Clinical Neurophysiology*, 34, 203-206.
- Békésy, G. von. (1960). *Experiments in Hearing*. New York: McGraw-Hill.
- Bickford, R.G., Jacobson, J.L., and Cody, D.T. (1964). Nature of averaged evoked potentials to sound and other stimuli in man. *Annals of New York Academy of Sciences*, 112, 204-223.
- Brinkmann, R.D., and Scherg, M. (1979). Human auditory on- and off-potentials of the brainstem. Influence of stimulus envelope characteristics. *Scandinavian Audiology*, 8, 27-32.
- Brown, C.J., and Abbas, P.J. (1987). A comparison of AP and ABR tuning curves in the guinea pig. *Hearing Research*, 25, 193-204.
- Brown, D.D., and Shallop, J.K. (1982). A clinically useful 500 Hz evoked response. *Nicolet Potentials*, 1, 9-12.
- Burkard, R. (1984). Sound pressure level measurement and spectral analysis of brief acoustic transients. *Electroencephalography and Clinical Neurophysiology*, 57, 83-91.
- Burkard, R., and Hecox, K. (1983). The effect of broadband noise on the human auditory evoked response. II. Frequency specificity. *Journal of the Acoustical Society of America*, 74, 1214-1223.

- Cody, A.R., and Russell, I.J. (1987). The responses of hair cells in the basal turn of the guinea-pig cochlea to tones. *Journal of Physiology*, 383, 551-569.
- Dallos, P. (1985). Response characteristics of mammalian cochlear hair cells. *The Journal of Neuroscience*, 5, 1591-1608.
- Dauman, R., Cazals, Y., and Aran, J-M. (1988). Frequency selectivity: reliability of electrocochleographic measure with iso-intensity masking. *Acta Otolaryngology*, 105, 50-55.
- Davis, H. (1976). Principles of electric response audiometry. *Annals of Otology, Rhinology and Laryngology*, 85(Suppl. 28), 1-96.
- Davis, H., and Hirsh, S.K. (1976). The audiometric utility of brain stem responses to low-frequency sounds. *Audiology*, 15, 181-195.
- Davis, H., and Hirsh, S.K. (1979). A slow brainstem response for low-frequency audiometry. *Audiology*, 18, 445-461.
- Davis, H., Hirsh, S.K., Popelka, G.R., and Formby, C. (1984). Frequency selectivity and thresholds of brief stimuli for electric response audiometry. *Audiology*, 23, 59-74.
- Davis, H., Hirsh, S.K., and Turpin, L.L. (1983). Possible utility of middle latency responses in electric response audiometry. *Advances in Oto-Rhino-Laryngology*, 31, 208-216.
- Davis, H., Hirsh, S.K., Turpin, L.L., and Peacock, M.E. (1985). Threshold sensitivity and frequency specificity in auditory brainstem response audiometry. *Audiology*, 24, 54-70.
- Dolan, T.G., and Klein, A.J. (1987). Effect of signal temporal shaping on the frequency specificity of the action potential in gerbils. *Audiology*, 26, 20-30.
- Dolan, T.G., Mills, J.H., and Schmiedt, R.A. (1985). Brainstem, whole-nerve AP and single-fiber suppression in the gerbil: Normative data. *Hearing Research*, 18, 203-210.

- Don, M., and Eggermont, J.J. (1978). Analysis of the click-evoked brainstem potentials in man using high-pass masking. *Journal of the Acoustical Society of America*, 63, 1084-1092.
- Don, M., Eggermont, J.J., and Brackmann, D.E. (1979). Reconstruction of the audiogram using brain stem responses and high-pass noise masking. *Annals of Otology, Rhinology and Laryngology*, 88(Suppl. 57), 1-20.
- Don, M., Elberling, C., and Waring, M. (1984). Objective detection of averaged auditory brainstem responses. *Scandinavian Audiology*, 13, 219-228.
- Don, M., Ponton, C.W., Eggermont, J.J., and Masuda, A. (1993). Gender differences in cochlear response time: An explanation for gender amplitude differences in the unmasked auditory brainstem response. *Journal of the Acoustical Society of America*, 94, 2135-2148.
- Durrant, J.D. (1983). Fundamentals of sound generation. In E.J. Moore (Ed.), *Bases of Auditory Brain-Stem Evoked Responses* (pp. 15-49). New York: Grune and Stratton.
- Durrant, J.D., Martin, W.H., Hirsch, B., and Schwegler, J. (1994). 3CLT ABR analyses in a human subject with unilateral extirpation of the inferior colliculus. *Hearing Research*, 72, 99-107.
- Egan, J.P., and Hake, H.W. (1950). On the masking pattern of a simple auditory stimulus. *Journal of the Acoustical Society of America*, 22, 622-630.
- Eggermont, J.J. (1976) Electrocochleography. In W.D. Keidel and W.D. Nelf (Eds.), *Handbook of Sensory Physiology*, Vol 5(3) (pp. 625-705). New York: Springer-Verlag.
- Eggermont, J.J. (1977). Compound action potential tuning curves in normal and pathologic ears. *Journal of the Acoustical Society of America*, 62, 1247-1251.

- Eggermont, J.J., and Don, M. (1980). Analysis of the click-evoked brainstem potentials in humans using high-pass noise masking. II. Effect of click intensity. *Journal of the Acoustical Society of America*, 68, 1671-1675.
- Eggermont, J.J., Spoor, A., and Odenthal, D.W. (1976). Frequency specificity of tone-burst electrocochleography. In R.J. Ruben, C. Elberling and G. Salomon (Eds.), *Electrocochleography* (pp. 215-246). Baltimore: University Park Press.
- Ehmer, R.H. (1959a). Masking patterns of tones. *Journal of the Acoustical Society of America*, 31, 1115-1120.
- Ehmer, R.H. (1959b). Masking by tones vs noise bands. *Journal of the Acoustical Society of America*, 31, 1253-1256.
- Elberling, C. (1974). Action potentials along the cochlear partition recorded from the ear canal in man. *Scandinavian Audiology*, 3, 13-19.
- Elberling, C. (1979a). Frequency composition of brain-stem auditory evoked potentials. *Scandinavian Audiology*, 8, 51-55.
- Elberling, C. (1979b). Auditory electrophysiology: Spectral analysis of cochlear and brain stem evoked potentials. A comment on: Kevanishvili and Aphonchenko: "Frequency composition of brain stem auditory evoked potentials". *Scandinavian Audiology*, 8, 57-64.
- Elberling, C., and Don, M. (1984). Quality estimation of averaged auditory brainstem responses. *Scandinavian Audiology*, 13, 187-197.
- Erwin, R., and Buchwald, J.S. (1986). Midlatency auditory evoked responses: Differential effects of sleep in the human. *Electroencephalography and Clinical Neurophysiology*, 65, 383-392.

- Evans, E.F. (1975). Cochlear nerve and cochlear nucleus. In W.D. Keidel and W.D. Neff (Eds.), *Handbook of Sensory Physiology, Vol 2, Auditory System Physiology (CNS), Behavioral Studies, and Psychoacoustics* (pp.2-108). New York: Springer-Verlag.
- Evans, E.F., and Elberling, C. (1982). Location specific components of the gross cochlear action potential. An assessment of the validity of the high-pass masking technique by cochlear nerve fiber recording in the cat. *Audiology*, 21, 204-227.
- Eysholdt, U., and Schreiner, C. (1982). Maximum length sequences - a fast method for measuring brainstem evoked responses. *Audiology*, 21, 242-250.
- Folsom, R.C. (1984). Frequency specificity of human auditory brainstem responses as revealed by pure-tone masking profiles. *Journal of the Acoustical Society of America*, 75, 919-924.
- Folsom, R.C., and Wynne, M.K. (1987). Auditory brain stem responses from human adults and infants: Wave V tuning curves. *Journal of the Acoustical Society of America*, 81, 412-417.
- Fowler, C.G., and Durrant, J.D. (1994). The effects of peripheral hearing loss on the auditory brainstem response. In J.T. Jacobson (Ed.), *Principles and Applications in Auditory Evoked Potentials* (pp. 237-250). Needham Heights: Allyn and Bacon
- Gabor, D. (1947). Acoustical quanta and the theory of hearing. *Nature*, 159, 591-595.
- Galambos, R., and Makeig, S. (1992). Physiological studies of central masking in man. I: The effects of noise on the 40-Hz steady-state response. *Journal of the Acoustical Society of America*, 92, 2683-2690.

- Galambos, R., Makeig, S., and Talmachoff, P.J. (1981). A 40-Hz auditory potential recorded from the human scalp. *Proceedings of the National Academy of Sciences (U.S.A.)*, 78, 2643-2647.
- Gerken, G.M., Moushegian, G., Stillman, R.D., and Rupert, A.L. (1975). Human frequency-following responses to monaural and binaural stimuli. *Electroencephalography and Clinical Neurophysiology*, 38, 379-386.
- Goldstein, R., Rodman, L.B., and Karlovich, R.S. (1972). Effect of stimulus rate and number on the early components of the averaged electroencephalic response. *Journal of Speech and Hearing Research*, 15, 559-566.
- Gorga, M.P., Beauchaine, K.L., Kaminski, J.R., and Bergman, B.M. (1992). Use of tone bursts in ABR evaluations. *American Journal of Audiology*, 1, 11-12.
- Gorga, M.P., Kaminski, J.R., Beauchaine, K.A., and Jesteadt, W. (1988). Auditory brainstem responses to tone bursts in normally hearing subjects. *Journal of Speech and Hearing Research*, 31, 87-97.
- Gorga, M.P., and Thornton, A.R. (1989). The choice of stimuli for ABR measurements. *Ear and Hearing*, 10, 217-230.
- Gott, P.S., and Hughes, E.C. (1989). Effect of noise masking on the brain-stem and middle-latency auditory evoked potentials: central and peripheral components. *Electroencephalography and Clinical Neurophysiology*, 74, 131-138.
- Gould, H.J., Crawford, M.R., Mendel, M.I., and Dodson, S.L. (1992). Quantification technique for the middle latency response. *Journal of the American Academy of Audiology*, 3, 153-158.
- Greenhouse, S.W., and Geisser, S. (1959). On methods in the analysis of profile data. *Psychometrika*, 24, 95-112.

- Greenwood, D.D. (1961). Auditory masking and the critical band. *Journal of the Acoustical Society of America*, 33, 484-502.
- Hari, R., Hämäläinen, M., and Joutsiniemi, S-L. (1989). Neuromagnetic steady-state responses to auditory stimuli. *Journal of the Acoustical Society of America*, 86, 1033-1039.
- Harker, L.A., Hosick, E., Voots, R.J., and Mendel, M.I. (1977). Influence of succinylcholine on middle component auditory evoked potentials. *Archives of Otolaryngology*, 103, 133-137.
- Harris, F.J. (1978). On the use of windows for harmonic analysis with the discrete Fourier transform. *Proceedings of the IEEE*, 66, 51-84.
- Hashimoto, I. (1982). Auditory evoked potentials from the human midbrain: slow brainstem responses. *Electroencephalography and Clinical Neurophysiology*, 53, 652-657.
- Hashimoto, I. (1984). Somatosensory evoked potentials from the human brain-stem: origins of short latency potentials. *Electroencephalography and Clinical Neurophysiology*, 57, 221-227.
- Hashimoto, I., Ishiyama, Y., Yoshimoto, T., and Nemoto, S. (1981). Brain-stem auditory-evoked potentials recorded directly from human brain-stem and thalamus. *Brain*, 104, 841-859.
- Hawkins, J.E., and Stevens, S.S. (1950). The masking of pure tones and of speech by white noise. *Journal of the Acoustical Society of America*, 22, 6-13.
- Hayes, D., and Jerger, J. (1982). Auditory brainstem response (ABR) to tone-pips: results in normal and hearing-impaired subjects. *Scandinavian Audiology*, 11, 133-142.
- Hyde, M.L. (1985). Frequency-specific BERA in infants. *Journal of Otolaryngology*, (Suppl. 14), 19-27.

Hyde, M.L., Matsumoto, N., and Alberti, P.W. (1987). The normative basis for click and frequency-specific BERA in high-risk infants. *Acta Otolaryngology*, 103, 602-611.

International Electrotechnical Commission. (1994). International Standard. Audiometers. Part 3: Auditory test signals of short duration for audiometric and neuro-otologic purposes.

Jacobson, J.T. (1983). Effects of rise time and noise masking on tone pip auditory brainstem responses. *Seminars in Hearing*, 4, 363-372.

Jewett, D.L. (1970). Volume-conducted potentials in response to auditory stimuli as detected by averaging in the cat. *Electroencephalography and Clinical Neurophysiology*, 28, 609-618.

Jewett, D.L., and Williston, J.S. (1971). Auditory-evoked far fields averaged from the scalp of humans. *Brain*, 94, 681-696.

Johnstone, B.M., Patuzzi, R., and Yates, G.K. (1986). Basilar membrane measurements and the travelling wave. *Hearing Research*, 22, 147-153.

Kavanagh, K.T., Harker, L.A., and Tyler, R.S. (1984). Auditory brainstem and middle latency responses. II. Threshold responses to a 500-Hz tone pip. *Annals of Otology, Rhinology and Laryngology*, 93, (Suppl. 108), 8-12.

Khanna, S.M., and Leonard, D.G.B. (1982). Basilar membrane tuning in the cat cochlea. *Science*, 215, 305-306.

Kiang, N.Y.S. (1965) *Discharge Patterns of Single Fibers in the Cat's Auditory Nerve*, Cambridge, Massachusetts: M.I.T. Press.

Kiang, N.Y.S. (1975). Stimulus representation in the discharge patterns of auditory neurons. In D.B. Tower (Ed.), *The Nervous System*,

- Vol 3: Human Communication and Its Disorders (pp. 81-96), New York: Raven Press.
- Kiang, N.Y.S., Liberman, M.C., Sewell, W.F., and Guinan, J.J. (1986). Single unit clues to cochlear mechanisms. *Hearing Research*, 22, 171-182.
- Kiang, N.Y.S., and Moxon, E.C. (1974). Tails of tuning curves of auditory-nerve fibers. *Journal of the Acoustical Society of America*, 55, 620-630.
- Kiang, N.Y.S., Sachs, M.B., and Peake, W.T. (1967). Shapes of tuning curves for single auditory-nerve fibers. *Journal of the Acoustical Society of America*, 42, 1341-1342.
- Kileny, P. (1981). The frequency specificity of tone-pip evoked auditory brain stem responses. *Ear and Hearing*, 2, 270-275.
- Kileny, P. (1983). Auditory evoked middle latency responses: current issues. *Seminars in Hearing*, 4, 403-413.
- Kileny, P.R., and Magathan, M.G. (1987). Predictive value of ABR in infants and children with moderate to profound hearing impairment. *Ear and Hearing*, 8, 217-221.
- Kileny, P., Paccioretti, D., and Wilson, A.F. (1987). Effects of cortical lesions on middle-latency auditory evoked responses (MLR). *Electroencephalography and Clinical Neurophysiology*, 66, 108-120.
- Kileny, P., and Shea, S.L. (1986). Middle-latency and 40-Hz auditory evoked responses in normal-hearing subjects: click and 500-Hz thresholds. *Journal of Speech and Hearing Research*, 29, 20-28.
- Klein, A.J. (1983). Properties of the brain-stem response slow-wave component. II. Frequency specificity. *Archives of Otolaryngology*, 109, 74-78.

- Klein, A.J., and Mills, J.H. (1981). Physiological (waves I and V) and psychological tuning curves in human subjects. *Journal of the Acoustical Society of America*, 69, 760-767.
- Klein, A.J., and Mills, J.H. (1981). Physiological and psychophysical measures from humans with temporary threshold shift. *Journal of the Acoustical Society of America*, 70, 1045-1053.
- Kodera, K., Marsh, R.R., Suzuki, M., and Suzuki, J-I. (1983). Portions of tone pips contributing to frequency-selective auditory brain stem responses. *Audiology*, 22, 209-218.
- Kodera, K., Yamane, H., Yamada, O., and Suzuki, J-I. (1977). Brain stem response audiometry at speech frequencies. *Audiology*, 16, 469-479.
- Kodera K., Yamane H., Yamada O., and Suzuki J-I. (1977). The effect of onset, offset and rise-decay times of tone bursts on brain stem response. *Scandinavian Audiology*, 6, 205-210.
- Kodera, K., Yamada, O., Yamane, H., and Suzuki, J-I. (1978). Effects of number and interstimulus interval of tone pips on fast responses. *Audiology*, 17, 500-510.
- Kramer, S.J. (1992). Frequency-specific auditory brainstem responses to bone-conducted stimuli. *Audiology*, 31, 61-71.
- Kraus, N., McGee, T., and Stein, L. (1994). The auditory middle latency response. In J.T. Jacobson (Ed.), *Principles and Applications in Auditory Evoked Potentials* (pp. 155-178). Needham Heights: Allyn and Bacon.
- Kraus, N., Reed, N., Smith, D.I., Stein, L., and Cartee, C. (1987). High-pass filter settings affect the detectability of MLRs in humans. *Electroencephalography and Clinical Neurophysiology*, 68, 234-236.
- Kraus, N., Smith, D.I., and McGee, T. (1987). Rate and filter effects on the developing middle-latency response. *Audiology*, 26, 257-268.

- Lane, R.H., Kupperman, G.L., and Goldstein, R. (1971). Early components of the averaged electroencephalic response in relation to rise-decay time and duration of pure tones. *Journal of Speech and Hearing Research*, 14, 408-415.
- Laukli, E. (1983). Stimulus waveforms used in brainstem response audiometry. *Scandinavian Audiology*, 12, 83-89.
- Laukli, E. (1983). High-pass and notch noise masking in suprathreshold brainstem response audiometry. *Scandinavian Audiology*, 12, 109-115.
- Laukli, E., Fjermedal, O., and Mair, I.W.S. (1988). Low-frequency auditory brainstem response threshold. *Scandinavian Audiology*, 17, 171-178.
- Laukli, E., and Mair, I.W.S. (1986). Frequency specificity of the auditory brainstem responses. A derived-band study. *Scandinavian Audiology*, 15, 141-146.
- Legatt, A.D., Arezzo, J.C., and Vaughan, H.G. (1986a). Short-latency auditory evoked potentials in the monkey. I. Wave shape and surface topography. *Electroencephalography and Clinical Neurophysiology*, 64, 41-52.
- Legatt, A.D., Arezzo, J.C., and Vaughan, H.G. (1986b). Short-latency auditory evoked potentials in the monkey. II. Intracranial generators. *Electroencephalography and Clinical Neurophysiology*, 64, 53-73.
- Legatt, A.D., Arezzo, J.C., and Vaughan, H.G. (1988). The anatomic and physiologic bases of brain stem auditory evoked potentials. *Neurologic Clinics*, 6, 681-704.
- Liberman, M.C. (1984). Single-neuron labeling and chronic cochlear pathology. I. Threshold shift and characteristic-frequency shift. *Hearing Research*, 16, 33-41.

- Liberman, M.C., and Kiang, N.Y.S. (1978). Acoustic trauma in cats. *Acta Otolaryngology*, (Suppl. 358), 10-22.
- Lichtenstein, V., and Stapells, D.R. (1995). The effective duration of the stimulus for the auditory brainstem and middle latency responses. Dissertation Proposal, Ph.D. Program in Speech and Hearing Sciences, City University of New York, New York.
- Mackersie, C., Down, K.E., and Stapells, D.R. (1993). Pure-tone masking profiles for human auditory brainstem and middle latency responses. *Hearing Research*, 65, 61-68.
- Martin, W.H., Pratt, H., and Schwegler, J.W. (1995). The origin of the human auditory brain-stem response wave II. *Electroencephalography and Clinical Neurophysiology*, 96, 357-370.
- McFarland, W.H., Vivion, M.C., and Goldstein, R. (1977). Middle components of the AER to tone pips in normal-hearing and hearing-impaired subjects. *Journal of Speech and Hearing Research*, 20, 781-798.
- McFarland, W.H., Vivion, M.C., Wolf, K.E., and Goldstein, R. (1975). Reexamination of effects of stimulus rate and number on the middle components of the averaged electroencephalic response. *Audiology*, 14, 456-465.
- Mendel, M.I. (1974). Influence of stimulus level and sleep stage on the early components of the averaged electroencephalic response to clicks during all night sleep. *Journal of Speech and Hearing Research*, 17, 5-17.
- Mendel, M.I. (1980). Clinical use of primary cortical responses. *Audiology*, 1980, 19, 1-15.
- Mendel, M.I., and Goldstein, R. (1971). Early components of the averaged electroencephalic response to constant level clicks during all-night sleep. *Journal of Speech and Hearing Research*, 14, 829-840.

- Mitchell, C., and Fowler, C. (1980). Tuning curves of cochlear and brainstem response in the guinea pig. *Journal of the Acoustical Society of America*, 68, 896-900.
- Møller, A.R., and Jannetta, P.J. (1982). Comparison between intracranially recorded potentials from the human auditory nerve and scalp recorded auditory brainstem responses (ABR). *Scandinavian Audiology*, 11, 33-40.
- Møller, A.R., and Jannetta, P.J. (1982). Evoked potentials from the inferior colliculus in man. *Electroencephalography and Clinical Neurophysiology*, 53, 612-620.
- Møller, A.R., Jannetta, P., Bennett, M., and Møller, M.B. (1981). Intracranially recorded responses from the human auditory nerve: New insights into the origin of brain stem evoked potentials (BSEPs). *Electroencephalography and Clinical Neurophysiology*, 52, 18-27.
- Møller, A.R., Jannetta, P., and Møller, M.B. (1982). Intracranially recorded auditory nerve response in man. New interpretations of BSER. *Archives of Otolaryngology*, 108, 77-82.
- Møller, A.R., Jannetta, P.J., and Sekhar, L.N. (1988). Contributions from the auditory nerve to the brain-stem auditory evoked potentials (BAEPs): results of intracranial recording in man. *Electroencephalography and Clinical Neurophysiology*, 71, 198-211.
- Moore, J.K. (1987). The human auditory brain stem as a generator of auditory evoked potentials. *Hearing Research*, 29, 33-43.
- Munnerley, G.M., Greville, K.A., Purdy, S.C., and Keith, W.J. (1991). Frequency-specific auditory brainstem responses: Relationship to behavioral thresholds in cochlear-impaired adults. *Audiology*, 30, 25-32.

- Musiek, F.E., and Guerink, N.A. (1981). Auditory brainstem and middle latency evoked response sensitivity near threshold. *Annals of Otolaryngology, Rhinology, and Laryngology*, 90, 236-240.
- Navaratnarajah, M., Thornton, C., Heneghan, C.P.H., and Jones, J.G. (1985). Effects of isoflurane in the auditory evoked responses in man. *British Journal of Anaesthesia*, 57, 352.
- Nousak, J.M.K., and Stapells, D.R. (1992). Frequency specificity of the auditory brain stem response to bone-conducted tones in infants and adults. *Ear and Hearing*, 13, 87-95.
- Nuttall, A.H. (1981). Some windows with very good sidelobe behavior. *IEEE Transactions on Acoustics, Speech, and Signal Processing*, 29, 84-91.
- Osterhammel, P.A., Shallop, J.K., and Terkildsen, K. (1985). The effect of sleep on the auditory brainstem response (ABR) and the middle latency response (MLR). *Scandinavian Audiology*, 14, 47-50.
- Özdamar, Ö., and Dallos, P. (1976). Input-output functions of cochlear whole-nerve action potentials: Interpretation in terms of one population of neurons. *Journal of the Acoustical Society of America*, 59, 143-147.
- Özdamar, Ö., and Kraus, N. (1983). Auditory middle-latency responses in humans. *Audiology*, 22, 34-49.
- Palaskas, C.W., Wilson, M.J., and Dobie, R.A. (1989). Electrophysiologic assessment of low-frequency hearing: sedation effects. *Otolaryngology-Head and Neck Surgery*, 101, 434-441.
- Parker, D.J., and Thornton, A.R.D. (1978a). The validity of the derived cochlear nerve and brainstem evoked responses of the human auditory system. *Scandinavian Audiology*, 7, 45-52.
- Parker, D.J., and Thornton, A.R.D. (1978b). Derived cochlear nerve and brainstem evoked responses of the human auditory system. The

- effect of masking in the derived band. *Scandinavian Audiology*, 7, 73-80.
- Pfeiffer, R.R. (1974). Consideration of the acoustic stimulus. In W.D. Keidel and W.D. Neffs (Eds.), *Handbook of Sensory Physiology*, Vol 1: Auditory System, Anatomy and Physiology (Ear) (pp. 9-38). New York: Springer-Verlag.
- Pickles, J.O. (1988). *An Introduction to the Physiology of Hearing*. (2nd ed.) New York: Academic Press.
- Picton, T.W. (1978). The strategy of evoked potential audiometry. In S.E. Gerber and G.T. Mencher (Eds.), *Early Diagnosis of Hearing Loss* (pp. 279-308). New York: Grune and Stratton.
- Picton, T.W., Champagne, S.C., and Kellett, A.J.C. (1992). Human auditory evoked potentials recorded using maximum length sequences. *Electroencephalography and Clinical Neurophysiology*, 84, 90-100.
- Picton, T.W., Hillyard, S.A., Krausz, H.I., and Galambos, R. (1974). Human auditory evoked potentials. I: Evaluation of components. *Electroencephalography and Clinical Neurophysiology*, 36, 179-190.
- Picton, T.W., Linden, R.D., Hamel, G., and Maru, J.T. (1983). Aspects of averaging. *Seminars in Hearing*, 4, 327-341.
- Picton, T.W., and Maru, J.T. (1984). Comments on obtaining signals from noise. In A. Starr, C. Rosenberg, M. Don, and H. Davis (Eds.), *Sensory Evoked Potentials. I. An International Conference on Standards for Auditory Brainstem Response (ABR) Testing* (pp. 147-151), Milan: Italy.
- Picton, T.W., Ouellette, J., Hamel, G., and Smith, A.D. (1979). Brainstem evoked potentials to tonepips in notched noise. *Journal of Otolaryngology*, 8, 289-314.

- Picton, T.W., Stapells, D.R., and Campbell, K.B. (1981). Auditory evoked potentials from the human cochlea and brainstem. *Journal of Otolaryngology*, 10, (Suppl. 9), 1-41.
- Picton, T.W., Woods, D.L., Baribeau-Braun, J., and Healey, T.M.G. (1977). Evoked potential audiometry. *Journal of Otolaryngology*, 6, 90-119.
- Plourde, G., Stapells, D.R., and Picton, T.W. (1991). The human auditory steady-state evoked potentials. *Acta Otolaryngologica*, (Suppl. 491), 153-160.
- Ponton, C.W., Don, M., and Eggermont, J.J. (1992). Place-specific derived cochlear microphonics from human ears. *Scandinavian Audiology*, 21, 131-141.
- Ponton, C.W., Eggermont, J.J., Coupland, S.G., and Winkelaar, R. (1992). Frequency-specific maturation of the eighth nerve and brain-stem auditory pathway: Evidence from derived auditory brain-stem responses (ABRs). *Journal of the Acoustical Society of America*, 91, 1576-1586.
- Portmann M., Harrison R.V., Negrevergne M., Dauman, R., and Aran, J-M. (1983). Electrocochleographic measures of cochlear frequency selectivity in hearing loss of cochlear origin. *Acta Otolaryngologica*, 95, 657-663.
- Purdy S., and Abbas P.J. (1989). Auditory brainstem response audiometry using linearly and Blackman gated tonebursts. *ASHA*, 31, 115-116.
- Purdy, S.C., Houghton, J.M., Keith, W.J., and Greville, K.A. (1989). Frequency-specific auditory brainstem responses. Effective masking levels and relationship to behavioral thresholds in normal hearing adults. *Audiology*, 28, 82-91.
- Rechtschaffen, A., and Kales, A. (1968). A manual of standardized terminology, techniques, and scoring system for sleep stages of

- human sleep. N.I.H. Publication 204, U.S. Govt. Printing Office, Washington, DC.
- Regan, D. (1982). Comparison of transient and steady-state methods. *Annals of the New York Academy of Sciences*, 388, 45-71.
- Robier, T.C., Fabry, D.A., Leek, M.R., and Van Summers, W. (1992). Improving the frequency specificity of the auditory brain stem response. *Ear and Hearing*, 13, 223-227.
- Robles, L., and Rhode, W.S. (1974) Nonlinear effects in the transient response of the basilar membrane. In E. Zwicker and E. Terhardt (Eds.), *Facts and Models in Hearing* (pp. 215-260). New York: Springer-Verlag.
- Robles, L., Ruggero, M.A., and Rich, N.C. (1986). Basilar membrane mechanics at the base of the chinchilla cochlea. I. Input-output functions, tuning curves, and response phase. *Journal of the Acoustical Society of America*, 80, 1364-1374.
- Rose, J.E., Brugge, J.F., Anderson, D.J., and Hind, J.E. (1967). Phase-locked responses to low-frequency tones in single auditory nerve fibers of the squirrel monkey. *Journal of Neurophysiology*, 30, 769-793.
- Rose, J.E., Hind, J.E., Anderson, D.J., and Brugge, J.F. (1971). Some effects of stimulus intensity on response of auditory nerve fibers in the squirrel monkey. *Journal of Neurophysiology*, 34, 685-699.
- Ruggero, M.A. (1992). Responses to sound of the basilar membrane of the mammalian cochlea. *Current Opinion in Neurobiology*, 2, 449-456.
- Ruggero, M.A., and Rich, N.C. (1991). Furosemide alters organ of corti mechanics: Evidence for feedback of outer hair cells upon the basilar membrane. *The Journal of Neuroscience*, 11, 1057-1069.

- Russell, I.J., and Sellick, P.M. (1978). Intracellular studies of hair cells in the mammalian cochlea. *Journal of Physiology*, 284, 261-290.
- Santarelli, R., Maurizi, M., Conti, G., Ottaviani, F., Paludetti, G., and Pettorossi, V.E. (1995). Generation of human auditory steady-state responses (SSRs). II. Addition of responses to individual stimuli. *Hearing Research*, 83, 9-18.
- Scharf, B. (1970). Critical bands. In J.V. Tobias (Ed.), *Foundations of Modern Auditory Theory*, Vol 1 (pp. 159-202). New York: Academic Press.
- Scherg, M. (1982). Distortion of the middle latency auditory response produced by analog filtering. *Scandinavian Audiology*, 11, 57-60.
- Scherg, M., and Volk, S.A. (1983). Frequency specificity of simultaneously recorded early and middle latency auditory evoked potentials. *Electroencephalography and Clinical Neurophysiology*, 56, 443-452.
- Scherg, M., and von Cramon, D. (1986). Evoked dipole source potentials of the human auditory cortex. *Electroencephalography and Clinical Neurophysiology*, 65, 344-360.
- Schimmel, H. (1967). The [+/-] reference: accuracy of estimating mean components in average response studies. *Science*, 157, 92-94.
- Schimmel, H., Rapin, I., and Cohen, M.M. (1974). Improving evoked response audiometry with special reference to the use of machine scoring. *Audiology*, 13, 33-65.
- Sellick, P.M., Patuzzi, R., and Johnstone, B.M. (1982). Measurement of basilar membrane motion in the guinea pig using the Mössbauer technique. *Journal of the Acoustical Society of America*, 72, 131-141.

- Skinner, P.H., and Antinoro, F. (1970). Critical-band theory and the auditory-evoked slow-wave V potential. *Journal of the Acoustical Society of America*, 48, 557-560.
- Smith, D.I., Mills, J.H., and Schmiedt, R.A. (1990). Frequency selectivity of the middle latency response. *Hearing Research*, 43, 95-106.
- Sohmer, H., and Kinarti, R. (1984). Survey of attempts to use auditory evoked potentials to obtain an audiogram. *British Journal of Audiology*, 18, 237-244.
- Stapells, D.R. (1984). Studies in evoked potential audiometry. Doctoral Dissertation, University of Ottawa, Ontario, Canada.
- Stapells, D.R. (1989). Auditory brainstem response assessment of infants and children. *Seminars in Hearing*, 10, 229-251.
- Stapells, D.R., Galambos, R., Costello, J.A., and Makeig, S. (1988). Inconsistency of auditory middle latency and steady-state responses in infants. *Electroencephalography and Clinical Neurophysiology*, 71, 289-295.
- Stapells, D.R., Gravel, J.S., and Martin, B.A. (1995). Thresholds for auditory brain stem responses to tones in notched noise from infants and young children with normal hearing or sensorineural hearing loss. *Ear and Hearing*, 16, 361-371.
- Stapells, D.R., Linden, D., Suffield, J.B., Hamel, G., and Picton, T.W. (1984). Human auditory steady state potentials. *Ear and Hearing*, 5, 105-113.
- Stapells, D.R., and Martin, B.A. (1993). Cochlear contributions to cortical ERPs to speech sounds /ba/ and /da/: A narrowband derived response study. Abstracts of the Thirteenth Congress of the International Electric Response Audiometry Study Group, 54.

- Stapells, D.R., and Picton, T.W. (1981). Technical aspects of brainstem evoked potential audiometry using tones. *Ear and Hearing*, 2, 20-29.
- Stapells, D.R., Picton, T.W., and Durieux-Smith, A. (1994). Electrophysiologic measures of frequency-specific auditory function. In J.T. Jacobson (Ed.), *Principles and Applications in Auditory Evoked Potentials* (pp. 251-283). Needham Heights: Allyn and Bacon.
- Stapells, D.R., Picton, T.W., Durieux-Smith, A., Edwards, C.G. and Moran, L.M. (1990). Thresholds for short-latency auditory-evoked potentials to tones in notched noise in normal-hearing and hearing-impaired subjects. *Audiology*, 29, 262-274.
- Stapells, D.R., Picton, T.W., Pérez-Abalo, M., Read, D., and Smith, A. (1985). Frequency specificity in evoked potential audiometry. In J.T. Jacobson (Ed.), *The Auditory Brainstem Response* (pp 147-177). San Diego: College-Hill Press.
- Stapells, D.R., Picton, T.W., and Smith, A.D. (1982). Normal hearing threshold for clicks. *Journal of the Acoustical Society of America*, 72, 74-79.
- Suzuki, J-I., Kodera, K., and Yamada, O. (1984). Brainstem response audiometry in newborns and hearing-impaired infants. In A. Starr, C. Rosenberg, M. Don, and H. Davis (Eds.) *Sensory Evoked Potentials. I. An International Conference on Standards for Auditory Brainstem Response (ABR) Testing* (pp. 85-93). Milan: Italy.
- Suzuki, T., Hirabayashi, M., and Kobayashi, K. (1984). Effects of analog and digital filtering on auditory middle latency response in adults and children. *Annals of Otology, Rhinology and Laryngology*, 93, 267-270.

- Suzuki, T., Hirai, Y., and Horiuchi, K. (1977). Auditory brain stem responses to pure tone stimuli. *Scandinavian Audiology*, 6, 51-56.
- Suzuki, T., Hirai, Y., and Horiuchi, K. (1981). Simultaneous recording of early and middle components of auditory electric response. *Ear and Hearing*, 2, 276-282.
- Suzuki, T., and Horiuchi, K. (1977). Effect of high-pass filter on auditory brain stem responses to tone pips. *Scandinavian Audiology*, 6, 123-126.
- Suzuki, T., and Horiuchi, K. (1981). Rise time of pure-tone stimuli in brain stem response audiometry. *Audiology*, 20, 101-112.
- Suzuki, T., and Kobayashi, K. (1984). An evaluation of 40-Hz event-related potentials in young children. *Audiology*, 23, 599-604.
- Suzuki, T., Kobayashi, K., and Hirabayashi, M. (1983). Frequency composition of auditory middle responses. *British Journal of Audiology*, 17, 1-4.
- Suzuki, T., Sakabe, N., and Miyashita, Y. (1982). Power spectral analysis of auditory brain stem responses to pure tone stimuli. *Scandinavian Audiology*, 11, 25-30.
- Takagi, N., Suzuki, T., and Kobayashi, K. (1985). Effect of tone-burst frequency on fast and slow components of auditory brain-stem response. *Scandinavian Audiology*, 14, 75-79.
- Telian, S.A., and Kileny, P.R. (1989). Usefulness of 1000 Hz tone-burst-evoked responses in the diagnosis of acoustic neuroma. *Otolaryngology, Head and Neck Surgery*, 101, 466-471.
- Terkildsen, K., Osterhammel, P., and Huis in't Veld, F. (1973). Electrocochleography with a far field technique. *Audiology*, 2, 141-148.

- Terkildsen K., Osterhammel P., and Huis in't Veld F. (1975).
Far-field electrocochleography. Frequency specificity of
the response. *Scandinavian Audiology*, 4, 167-172.
- Thornton, C., Catley, D.M., Jordan, C., Lehane, J.R., Royston, D., and
Jones, J.G. (1983). Enflurane anaesthesia causes graded changes
in the brainstem and early cortical auditory evoked response in
man. *British Journal of Anaesthesia*, 55, 479-486.
- Thornton, C., Heneghan, C.P.H., James, M.F.M., and Jones, J.G. (1984).
Effects of halothane or enflurane with controlled ventilation on
auditory evoked potentials. *British Journal of Anaesthesia*, 56,
315-323.
- Thornton, C., Heneghan, C.P.H., Navaratnarajah, M., Bateman, P.E., and
Jones, J.G. (1985). Effect of etomidate on the auditory evoked
response in man. *British Journal of Anaesthesia*, 57, 554-561.
- Thornton, C., Heneghan, C.P.H., Navaratnarajah, M., and Jones, J.G.
(1985). The selective effect of althesin on the auditory evoked
response in man. *British Journal of Anaesthesia*, 57, 575-578.
- Thornton, A.R., Mendel, M.I., and Anderson, C.V. (1977). Effects of
stimulus frequency and intensity on the middle components of the
averaged auditory electroencephalic response. *Journal of Speech
and Hearing Research*, 20, 81-94.
- Tonndorf, J. (1970). Cochlear mechanics and hydro-dynamics. In J.V.
Tobias (Ed.), *Foundations of Modern Auditory Theory*, Vol 1 (pp.
205-254). New York: Academic Press.
- Tonndorf, J. (1973) Cochlear nonlinearities. In A.R. Møller (Ed.),
Basic Mechanisms of Hearing (pp. 11-47). New York: Academic Press.
- Trees, D.E., and Turner, C.W. (1986). Spread of masking in normal
subjects and in subjects with high-frequency hearing loss.
Audiology, 25, 70-83.

- Valdes-Sosa, M.J., Bobes, M.A., Pérez-Abalo, M.C., Perera, M., Carballo, J.A., and Valdez-Sosa, P. (1987). Comparison of auditory-evoked potential detection methods using signal detection theory. *Audiology*, 26, 166-178.
- Vaughan, H.G., and Ritter, W. (1970). The sources of auditory evoked responses recorded from the human scalp. *Electroencephalography and Clinical Neurophysiology*, 28, 360-367.
- Vivion, M.C., Hirsch, J.E., Frye-Osier, J.L., and Goldstein, R. (1980). Effects of stimulus rise-fall time and equivalent duration on middle components of AER. *Scandinavian Audiology*, 9, 223-232.
- Ward, W.D., Gloorig A., and Sklar D.L. (1958). Relation between recovery from temporary threshold shift and duration of exposure. *Journal of the Acoustical Society of America*, 31, 600-602.
- Weber, B.A. (1987). Assessing low frequency hearing using auditory evoked potentials. *Ear and Hearing*, 8(Suppl.4), 49-54.
- Wong, P.K.H., and Bickford, (1980). Brainstem auditory evoked potentials: The use of noise estimate. *Electroencephalography and Clinical Neurophysiology*, 50, 25-34.
- Woods, D.L., Clayworth, C.C., Knight, R.T., Simpson, G.V., and Naeser, M.A. (1987). Generators of middle- and long-latency auditory evoked potentials: implications from studies of patients from bitemporal lesions. *Electroencephalography and Clinical Neurophysiology*, 68, 132-148.
- Woods, D.L., Knight, R.T., and Neville, H.J. (1984). Bitemporal lesions dissociate auditory evoked potentials and perception. *Electroencephalography and Clinical Neurophysiology*, 57, 208-220.
- Wu, C-Y., and Stapells, D.R. (1994). Pure-tone masking profiles for human auditory brainstem and middle latency responses to 500-Hz tones. *Hearing Research*, 78, 169-174.

Wu, C-Y., and Stapells, D.R. (in preparation). Detection of auditory
brainstem and middle latency responses to clicks and brief tones.

I: Expert human observers.

VITA

Margaret "Peggy" Oates received her Bachelor of Arts degree in Communication Disorders with a minor in Psychology from the University of Vermont in May, 1980. She obtained her Masters of Science in Audiology from Teachers College, Columbia University, New York in January of 1982. A clinical audiologist for over thirteen years, Peggy has served as the Supervisor of Audiology at Manhattan Eye, Ear, and Throat Hospital in New York, N.Y. from 1987-1994. She has also been an Instructor in Audiology at Adelphi University in Garden City, New York, and is presently employed as a research audiologist in the Auditory Evoked Potentials Laboratory at the Albert Einstein College of Medicine, Bronx, New York.

Peggy's dissertation supervisor was David R. Stapells, Ph.D. Her dissertation research was financially supported by an American Speech-Language-Hearing Foundation Student Research grant (1993) as well as by NIDCD grant 8P50 DC00223 (to Dr. Stapells).

AWARDS/GRANTS

American Speech-Language-Hearing Foundation Student Research Grant (1993).

MANUSCRIPTS:

Oates, P. Sudden sensorineural hearing loss. NYSSLHA Communicator, 1988. 3(2),15. [Abstract]

Oates, P. and Stapells, D.R. Cochlear hearing loss and the auditory brainstem response (ABR): Influence of click intensity and patient gender. Audiology Today, 1990, 2(2), 34. [Abstract]

Stapells, D.R. and Oates, P. Influence of click intensity and patient gender on the effect of cochlear hearing loss on the auditory brainstem response (ABR). Otolaryngology-Head and Neck Surgery, 1990, 103, 232. [Abstract]

Oates, P. and Stapells, D.R. (1992). Interaction of click intensity and cochlear hearing loss on auditory brainstem response wave V latency. Ear and Hearing, 13, 28-34.

Oates, P. and Stapells, D.R. (1995). Cochlear contributions to the human auditory brainstem and middle latency responses to 500- and 2000-Hz linear versus Blackman-windowed tones. Abstracts of the 18th Midwinter Meeting of the Association for Research in Otolaryngology, 137.

Oates, P. Unraveling the mysteries of conducting tone ABRs. NYSSLHA Communicator, 1995, 4(2) 40. [Abstract]

Oates, P. and Stapells, D.R. (1995). Cochlear contributions to the human auditory brainstem and middle latency responses to 500- and 2000-Hz linear- versus Blackman-windowed tones. Audiology, (in press). [Abstract]

Oates, P. (1995). Frequency specificity of the Auditory Brainstem and the Middle Latency Responses. Doctoral dissertation, City University of New York, New York, New York

Oates, P. and Stapells, D.R. (in preparation). Cochlear contributions to the human auditory brainstem and middle latency responses to brief tones.

PRESENTATIONS

Oates, P. Director of course entitled "Clinical Applications of Electrophysiology" and moderator of "Panel discussion: Case histories in oto-acoustic emissions, electrocochleography, and electric acoustic reflexes", given at Manhattan Eye, Ear and Throat Hospital, N.Y., June 4, 1993.

Oates, P. "Unraveling the mysteries of conducting tone ABRs" given at the 35th annual convention of New York State Speech-Language-Hearing Association, New York, N.Y., April 29, 1995.