

Some Factors that May Influence the Accuracy of Auditory Brainstem Response Estimates of Hearing Loss

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Introduction

There has always been a need for objective tests that assess auditory function in infants, young children, and/or any patient whose developmental level precluded the use of behavioral audiometric techniques. Although several approaches have been tried, such as acoustic-reflex threshold, middle-latency response, and late auditory-evoked potential measurements, for the past twenty-five years, that need has been met primarily by the measurement of short-latency auditory-evoked potentials, primarily the auditory brainstem response (ABR). These responses arise from the synchronous discharges from groups of neurons along the lower auditory pathway. As such, they are more easily resolved when the eliciting stimulus is characterized by a rapid onset. These responses also must be resolved in a background of noise, coming from other ongoing neural activity. The combination of stimuli with rapid onsets, which results in the synchronized discharge of responses from several neurons, and time-averaging, locked to the stimulus presentation, helps to resolve these low-level auditory-evoked potentials.

There are many papers and several reviews currently available describing the use of the ABR to estimate the magnitude and configuration of hearing loss (see, for example, Stapells 2000; Stapells, Picton, Perez-Abalo, Read and Smith 1985; Stapells, Picton and Durieux-Smith 1994; Stapells and Oates 1997; Gorga 1999; Hall 1992, for reviews of the topic). Indeed, there is little new information on ABRs since these reviews were published. What is new is the use of steady-state evoked potentials, which is the topic of

a separate chapter associated with the Phonak conference on amplification for infants and young children (Picton et al. 2002). Instead of re-iterating a review of ABR measurements, which already exists in several other published sources, this chapter will focus on underlying issues that may be important to understand whenever one attempts to describe auditory function on a frequency-by-frequency (or cochlear place-by-place) basis. Stapells (2000), in a review chapter associated with the First International Conference on Amplification in infants and children, provided a nice review of previous data and a description of stimulus and recording conditions to be considered when the ABR is used to estimate hearing loss. The reader interested in more practical details is referred to his chapter. In an effort to provide a unique or, at least, different slant on the issues, this chapter will focus on more basic mechanisms. Thus, the focus here will be directed towards stimulus issues and underlying cochlear physiology in ears with normal hearing and ears with hearing loss.

Stimulus Frequency Specificity

Clicks

There is an exact correspondence between the time waveform and the amplitude and phase spectra of stimuli. For the purposes of ABR measurements, we are more concerned with the amplitude spectra. To a first approximation, the duration of a sound will determine the width of the main or primary energy lobe, and the rise/fall time will determine the rate at which energy decreases with increasing frequency. As a general rule, the shorter the rise/fall time and/or duration, the broader the amplitude spectrum. For example, the electrical spectrum for a 100- μ s click

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will have spectral zeros (frequencies at which the energy is reduced) every 10 kHz (1 divided by the duration), and the spectral level (level as a function of frequency) above the first spectral zero will decrease with a slope of 6 dB per octave. This electrical signal will be shaped or filtered as it is transduced into an acoustical signal. The frequency response of the loudspeaker/earphone will limit the bandwidth of the energy in the acoustic spectrum; for most transducers in clinical use (TDH39, TDH49, TDH50, ER3A), the acoustic stimulus is limited to frequencies below 10 kHz. While none of these transducers have perfectly flat frequency responses (even within their passbands), when excited by a brief rectangular wave (a click), the acoustic spectra they produce will have roughly equivalent energy at all frequencies within their passband. This means that a wide range of cochlear places may be excited when a click is presented. Theoretically, a click-evoked response may include discharges from neurons innervating the entire cochlea. Herein lies the principle advantage and limitation of using clicks to predict cochlear status. Clicks typically elicit robust responses because of their rapid onsets and broad spectra, which help to synchronize the discharges of many nerve fibers. This results in a response that is more easily measured in a background of ongoing, unrelated neural activity (noise). However, those same rapid onsets and brief durations (with their associated broad spectra) result in stimuli that are capable of exciting broad cochlear regions; thus, any measured response cannot be assigned with certainty to a specific cochlear place. In spite of this fact, relations between click-evoked ABR thresholds and behavioral thresholds have been described, suggesting that, although characterized by variability, these thresholds correlate with the average behavioral thresholds for 2 and 4 kHz (eg. Jerger and Mauldin 1978; Gorga, Worthington, Reiland, Beauchaine and Goldgar 1985; van der Drift, Brocaar and van Zaanen 1987). This relation between click-evoked ABR thresholds and pure-tone thresholds at 2 and 4 kHz may relate to the increased synchrony of discharges from neurons innervating basal cochlear regions, compared to the greater temporal dispersion of discharges for neurons innervating more apical regions of the cochlea (see figure 6, Kiang 1975, for a demonstration of this effect). It is noteworthy that clicks have been used as the stimulus in some universal newborn hearing screening (UNHS) programs in which the screening measure is an ABR. The observation of a click-evoked ABR at a low level (say,

30 to 40 dB nHL) typically is viewed as indicative of normal cochlear function. At the very least, such responses would result in a UNHS pass, and no referral would be made for follow-up testing. Presumably, the correlations between click-evoked ABR thresholds and behavioral thresholds is sufficient to lead to the conclusion that a click-evoked ABR at 30–40 dB nHL rules out educationally significant hearing loss; thus, further testing usually is not recommended under these conditions. As an aside, test performance for UNHS measures (both ABR and OAE) is difficult to establish, especially in terms of test sensitivity, due to the low prevalence of congenital hearing loss and the need for follow-up testing on all infants regardless of whether they pass or refer (Gorga, Preissler, Simmons, Walker and Hoover 2001). Even those studies that have attempted to estimate test performance (Norton et al. 2000) viewed their results cautiously because of the small number of infants with hearing loss in their sample.

Tone Bursts

While clicks provide information about cochlear status and may be useful stimuli when applied to screening, they may not provide information with sufficient detail that would allow one to characterize the magnitude and configuration of hearing loss. Several techniques have been developed to meet this need for more “frequency-specific” or “place-specific” information, including the derived-band technique (eg., Don, Eggermont and Brackman 1979), the notched-noise technique (eg., Stapells, Gravel and Martin 1995), and tone bursts in quiet (eg., Gorga, Reiland, Beauchaine and Jesteadt 1988; Gorga and Thornton 1989). Data are available that suggest that all three approaches provide reasonably accurate estimates of hearing loss as a function of frequency. Since gated sinusoids are in common clinical use when ABR measurements are used to determine the magnitude and configuration of hearing loss, spectral characteristics of tone bursts will be described next.

Just as there is an exact relationship between the time waveform and amplitude and phase spectra of a click, a similar relationship exists for tone bursts. As a general, first-order rule, the duration of a tone burst determines the width of energy lobes in its spectrum and the rise/fall time determines the relation between the level in the main energy lobe (centered over the nominal frequency) and the level in the side lobes (both above and below the main energy lobe). Thus,

short-duration tone bursts will have wide energy lobes and long-duration tone bursts will have narrow lobes. Tone bursts with rapid onsets will have less level difference between the main energy lobe and side lobes, compared to the same tone burst with longer rise/fall times.

While these general rules are true, it is important to remember that onset responses, like the ABR, are elicited by the earliest portions of the stimulus, not by the steady-state portion, especially for longer duration tone bursts. Figure 1 provides a schematic representation of the response from an auditory neuron (in a lower animal) to a 100-ms tone burst. The number of spikes or discharges is plotted as a function of time. These plots are called post-stimulus time (PST) histograms. Note that, prior to stimulation, the nerve fiber is spontaneously active. In response to a stimulus, there is rapid increase in discharges at stimulus onset, followed by a drop to a steady discharge rate

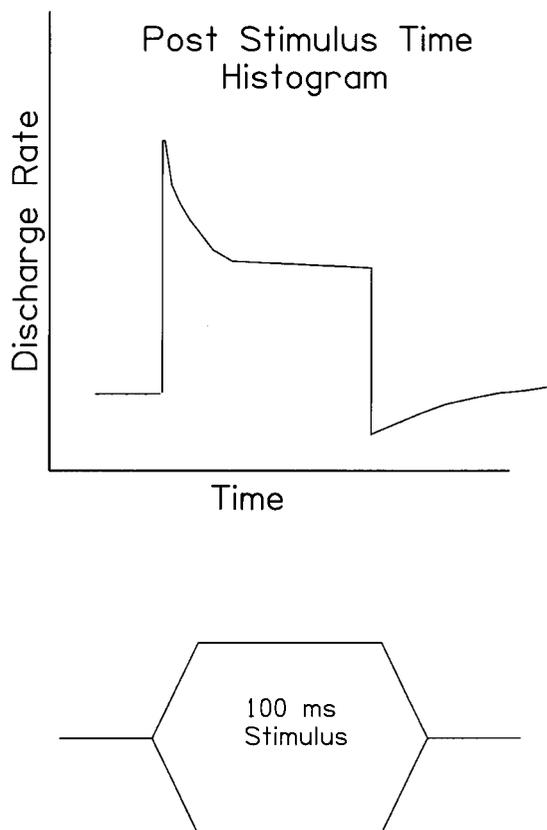


Figure 1. Top: Discharge rate as a function of time (post-stimulus time histogram, PST) for an individual auditory nerve fiber. Bottom: Envelope of a 100-ms stimulus exciting this nerve fiber.

that is above the spontaneous rate but below the rate at stimulus onset. Thus, the nerve fiber responds throughout the stimulation, but at different rates at stimulus onset compared to the steady-state portion of the stimulus. This change in discharge rate is referred to as perstimulatory short-term adaptation, and is a characteristic of auditory-nerve fibers.

Returning to ABR measurements, one could generate a tone burst with an instantaneous rise/fall time and 100-ms duration that would be effective at eliciting an ABR. This stimulus would have a relatively narrow, long-term amplitude spectrum, and one might conclude, erroneously, that it was providing cochlear place-specific information because spectral analyses indicated that the energy was concentrated at the nominal center frequency. However, its spectrum at stimulus onset (the portion of the stimulus responsible for eliciting short-latency, onset responses like the ABR) would be broad, and, thus, would be capable of eliciting a response from a wide region of the cochlea. As a result, one should be careful when selecting the temporal characteristics for stimuli, recognizing that the short-term spectral characteristics during the earliest portions of the stimulus are more important for ABRs than the long-term spectrum of the stimulus. Manipulations of the steady-state or "plateau" portion of a tone burst may not result in a stimulus that is better defined in the frequency domain relative to the response during ABR measurements.

However, the spectral characteristics at stimulus onset and offset depend, not only on the rise/fall time, but also on the manner in which tone bursts are turned on and off (Nuttall 1981; Harris 1978). Rise time is the time it takes a stimulus to go from zero to its maximum amplitude; fall time is the time it takes to reverse this process. There are several ways that this can be accomplished. Early clinical ABR systems that provided tone-burst stimuli only provided Bartlett (linear) gating functions, in which the stimulus grew from zero to maximum amplitude on a straight line. Linear windows have slope discontinuities (sharp edges) at their beginning and at their peak, which result in a "splatter" of energy to adjacent frequencies. The spectra for linearly-gated tone bursts are characterized by side-lobe levels that are 27 dB below the level in the main energy lobe, and continue to decrease in level at a rate of 12 dB/octave as one moves further away in frequency. This means that the stimulus includes energy at the nominal center frequency, but also at other frequencies that

potentially could excite distant cochlear regions. More recent evoked-potential systems provide other windowing functions that attempt to reduce these discontinuities, which would reduce the splatter of energy to adjacent frequencies and, thus, result in stimuli that are more sharply defined in the frequency domain. One of these windowing functions, the Blackman window, is characterized by side-lobe levels that are 58 dB below the level in the main energy lobe. Energy continues to decrease beyond this point at a rate of 18 dB/octave. Thus, less energy exists at frequency other than those centered over the nominal center frequency. In the case of both Bartlett and Blackman windows (as well as other windowing functions), the above spectral characteristics hold only for the case in which no plateau exists. These descriptions do not apply when plateaus are added, which result in more complex and potentially more dispersive spectral composition. Figure 2 shows time waveforms and amplitude spectra for 4-kHz tone bursts gated with Bartlett (linear) and Blackman windows. In both cases, the rise/fall times were 1 ms and there was no plateau. Subtle differences can be observed in the time waveforms of these stimuli (insets). More importantly, the linearly-gated tone burst has a more narrow main energy lobe (centered over 4 kHz), but also has a richer side-lobe structure. The Blackman-gated tone burst, on the other hand, has a slightly wider main energy lobe, but greater reduction of side-lobe energy relative to the energy in the lobe centered at 4 kHz. Although there is some debate as to whether this stimulus results in more cochlear place-specific responses, compared to linearly-gated tone bursts (Oates and Stapells 1997a, 1997b; Purdy and Abbas 1989), all other things being equal, it should be the case that it would be less likely that responses elicited by Blackman-gated tone bursts will be derived from cochlear regions distant from the place where the nominal center frequency is represented, compared to the response elicited by linearly-gated tone bursts.

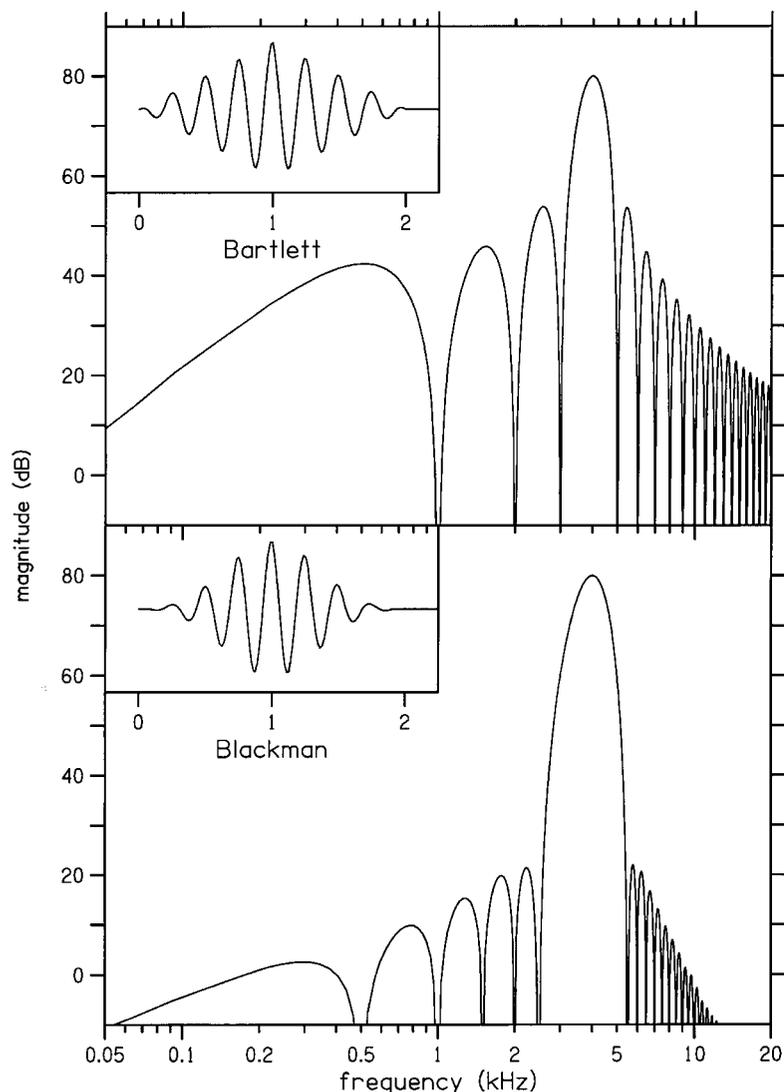


Figure 2. Time waveforms (insets) and amplitude spectra for 4-kHz tone bursts having 1 ms each on the rise and fall time, with no plateau (2 ms total duration). Top panel represents the waveform and spectrum for a Bartlett (linear) window. Bottom panel represents the waveform and spectrum for a Blackman window.

Masking Noise

Several papers recommend the use of notched-noise maskers in an effort to restrict the measured response to those cochlear regions associated with the center of the notch in the noise (eg., Picton, Ouellette, Hamel and Smith 1979; Stapells et al. 1995). In this paradigm, broadband noise is filtered in order to create a notch or frequency region of reduced energy, into which a tone burst is placed, whose nominal

frequency is at the center frequency of the notch. The energy at frequencies away from the notch in these maskers should “occupy” the responses from nerve fibers innervating the corresponding cochlear places where distant frequencies are represented. Those nerve fibers innervating cochlear regions corresponding to frequencies within the notch should be free to respond to the tone burst that contains energy at those frequencies. While data support the use of notched-noise maskers when using ABR measurements to estimate hearing loss on a frequency-specific basis (e.g., Stapells et al. 1995), complex interactions between these maskers and cochlear response properties within the notch may occur (e.g., Abbas and Sachs 1976; Costalupes, Rich and Ruggero 1987; Delgutte 1990; Ruggero, Robles and Rich 1992), and these interactions will differ between normal and impaired ears (Dallos, Harris, Relkin and Cheatham 1980; Schmiedt and Zwislocki 1980). For example, noise energy might exert a suppressive effect on responses coming from fibers innervating cochlear regions within the notch where no noise is present. This effect would be expected to occur only if hearing within the notch is normal, because suppressive effects (like other normal nonlinear phenomena) occur only in cases when cochlear function is normal. Suppressive effects are reduced or absent when outer hair cell damage (i.e., hearing loss) exists.

In spite of issues associated with cochlear response properties, there are several circumstances in which the use of notched noise would be valuable. If the stimulus is not well defined in the frequency domain, side-lobe energy in it could directly excite distant cochlear regions, when hearing is significantly better than it is at the nominal tone-burst frequency. This would occur when a gated tone burst with a short rise time is used in an ear with differences in sensitivity as a function of frequency that exceed the side-lobe reduction of the specific windowing function. The energy in the notched-noise masker at these same distant frequency regions would also directly excite the cochlear places corresponding to these distant frequencies, but the excitation would not be synchronized to the averaging. As a consequence, the responses from individual neurons innervating these distant regions would contribute randomly to the time-locked, averaged response. Thus, noise maskers should be effective in eliminating the contributions from more normal cochlear regions that are directly excited by energy in the stimulus that is distant from the nominal center

frequency. The problem of direct excitation of distant cochlear regions by energy in the tone bursts could be addressed, at least in part, by generating tone bursts with more narrowly defined amplitude spectra. It is for this reason that we favor tone bursts gated with Blackman windows when attempting to describe cochlear function in a more place-specific manner.

Masking approaches also should be useful when hearing is more normal for high frequencies (basal cochlear regions) compared to lower frequencies. When the hearing loss is restricted to lower frequencies, an intense, low-frequency stimulus could excite more normal high-frequency regions due to basal spread of excitation (see below for a discussion of cochlear physiology in normal and impaired ears). Even when hearing is completely normal, an intense low-frequency sound will spread its excitation towards higher frequency, basal cochlear regions. A notched-noise masker (or a high-pass masker, for that matter) should “occupy” the fibers innervating these normal high-frequency regions; thus, any measured response presumably should be derived from nerve fibers innervating cochlear regions corresponding to the nominal center frequency of the stimulus.

It is unclear, however, how notched-noise or high-pass noise maskers will serve this same purpose when hearing loss is greater in the higher frequencies, compared to lower frequencies. Under these conditions, the effectiveness of the masker (which is being used to eliminate responses due to basal spread of excitation) will be reduced due to the threshold elevations for the frequencies represented in the masker. In fact, changes in cochlear physiology make it difficult to describe cochlear place-specific response properties once hearing loss exists, regardless of whether tone bursts (however windowed) or pure tones are used; unfortunately, combining gated sinusoids with maskers does not solve the problem. These problems exist equally for behavioral threshold assessments as they do for evoked potential measurements. A more detailed discussion of these issues is deferred to a subsequent section of this chapter in which cochlear physiology in normal and impaired ears is described.

Calibration of Stimulus Level

There is no American National Standards Institute (ANSI) standard for calibrating the stimuli

typically used in ABR measurements. As a consequence, most centers either accept the calibration values provided by the manufacturer of the device or perform a biological calibration. It should be noted that, in all likelihood, the calibration values provided by manufacturers are themselves based on biological calibrations, in which behavioral thresholds for ABR stimuli are measured in subjects with normal hearing, the mean behavioral thresholds for these subjects is taken as the reference level (i.e., 0 dB nHL), and the associated SPLs are stored into a calibration table in the device's software. If a patient then produces an ABR threshold of 50 dB nHL, it is assumed that the patient has a moderate hearing loss. Fundamentally, there is nothing wrong with this calibration procedure and, in the absence of an ANSI standard, it represents a reasonable approach for setting stimulus levels.

However, there are some factors that one might wish to consider when developing and using biological calibrations to set stimulus levels. A goal of establishing an "audiometric zero" is to have a reference that is equivalent in some way to audiometric zero as stated in the ANSI standard for pure-tone audiometry (ANSI S3.2 1996). For the purposes of performing biological calibrations of ABR stimuli, normal hearing typically is defined as pure-tone thresholds of 10 dB HL or better (re: ANSI S3.2 1996), or something close to that criterion. However, 10 dB HL is 10 dB greater than 0 dB HL. This means that a biological calibration, based on ears with thresholds of 10 dB HL would exceed the value for audiometric zero by 10 dB. For example, if the reference equivalent threshold (0 dB HL re: ANSI 1996) for a specific earphone occurs at 10 dB SPL at 2 kHz, then the biological calibration based on a subject with a pure-tone threshold of 10 dB HL would be 20 dB SPL. Thus, there might be some value in taking into account the extent to which individual normal-hearing subjects' thresholds deviate from pure-tone audiometric zero (Gorga, Kaminski, Beauchaine and Bergman 1993). By correcting for that deviation, one might establish a reference closer to 0 dB HL re: ANSI standards.

Reference equivalent threshold levels for pure tones (as specified in ANSI standards) are based on a biological calibration of long-duration stimuli. These behavioral thresholds are affected by stimulus duration, a process known as temporal integration. As stimulus duration increases (say from 1 ms to 200

ms), behavioral thresholds decrease roughly by a factor of 10 dB for every tenfold increase in duration in ears with normal hearing (e.g., Garner 1947; Plomp and Bouman 1959; Watson and Gengel 1969). ANSI standards are based on the thresholds to stimuli that are long relative to the durations for which temporal integration is observed. By way of illustration, audiometric zero, based on the ANSI standard, might be 10 dB SPL (depending on earphone) for a 2-kHz pure tone; in contrast, the normal behavioral threshold for a 2 kHz tone burst of 2 ms duration might be 30 dB SPL, or 20 dB higher, due to temporal integration.

There are two reasons why this temporal integration effect might be relevant when one considers the calibration of ABR stimuli. For normal-hearing subjects, on whom biological calibrations are based, there might be a 20-dB difference between their pure-tone behavioral thresholds and their behavioral thresholds to a stimulus that might be used when measuring ABRs, depending on stimulus rate. Furthermore, ABRs are onset responses, being elicited only by the earliest portions of the stimulus. Stimulus duration has little or no effect on ABR threshold because temporal integration is not relevant for onset responses (e.g., Gorga, Beauchaine, Reiland, Worthington and Javel 1984). Finally, temporal integration typically is reduced or absent in ears with hearing loss (e.g., Gengel and Watson 1971; Wright 1968). In ears with cochlear hearing loss, there may be little or no difference between their pure-tone and their brief-tone audiometric thresholds, unlike ears with normal hearing, where differences of 15–20 dB are observed. As an aside, a parsimonious explanation for the reduced temporal integration in ears with hearing loss might attribute the effect to the loss of peripheral compressive nonlinearity, and not to changes in temporal resolution (Oxenham and Plack 2000; Oxenham 2001). Biological calibrations based on normal thresholds to brief stimuli, therefore, might result in a slight underestimation of pure-tone thresholds in ears with hearing loss. The magnitude of this effect, however, cannot exceed the maximum temporal integration effect, which seldom exceeds 20 dB. Furthermore, this problem may occur only for ears with normal hearing, in which temporal integration is expected. It may matter less in ears with hearing loss, for which pure-tone and brief-tone thresholds are more equivalent.

Cochlear Frequency Resolution

Thus far, the focus of the discussion has been on the characteristics of the stimuli used to elicit ABRs. As hinted to in the previous discussion, these stimulus characteristics should be considered in relation to the known frequency-resolving capabilities of the cochlea, both in its normal and its impaired states. A brief discussion of cochlear frequency selectivity in normal and impaired ears may help to determine the choices one makes when using the ABR to determine magnitude and configuration of hearing loss.

Normal Cochlear Frequency Selectivity

In its normal state, every place along the cochlear partition is highly tuned in that each place is sensitive (i.e., has low thresholds) to frequencies that are maximally represented at that specific place, and less sensitive (has higher thresholds) for stimuli whose frequencies are progressively more distant from the best or characteristic frequency (CF) for that place. Furthermore, high frequencies are maximally represented at the basal end of the cochlea; as frequency decreases, the maximum representation systematically moves towards the apex. This mapping of frequency to place is called tonotopic organization. Finally, the spread of excitation as intensity increases is asymmetrical, with greater spread towards basal (high-frequency) regions from intense low-frequency stimulation. Intense high-frequency stimulation results in little or no spread of excitation towards more apical (lower frequency) regions.

The top panel of figure 3 provides an idealized representation of a normal frequency threshold curve (FTC) for an individual auditory-nerve fiber; FTCs are plots of threshold as a function of frequency (for just a few of the many examples of FTCs from normal and impaired ears, see Kiang, Watanabe, Thomas and Clark 1965; Kiang and Moxon 1974; Kiang, Liberman and Levine 1976; Dallos and Harris 1978; Liberman 1978; Liberman and Dodds 1984). These threshold versus frequency plots are sometimes called single-unit tuning curves in that they represent the “tuning” at a specific place along the cochlea. In the normal case, the lowest threshold occurs at CF, with threshold increasing rapidly as one moves towards higher or lower frequencies relative to CF. Note that on the low-frequency side, thresholds increase up to a point, and then remain relatively constant as frequency decreases further. When the

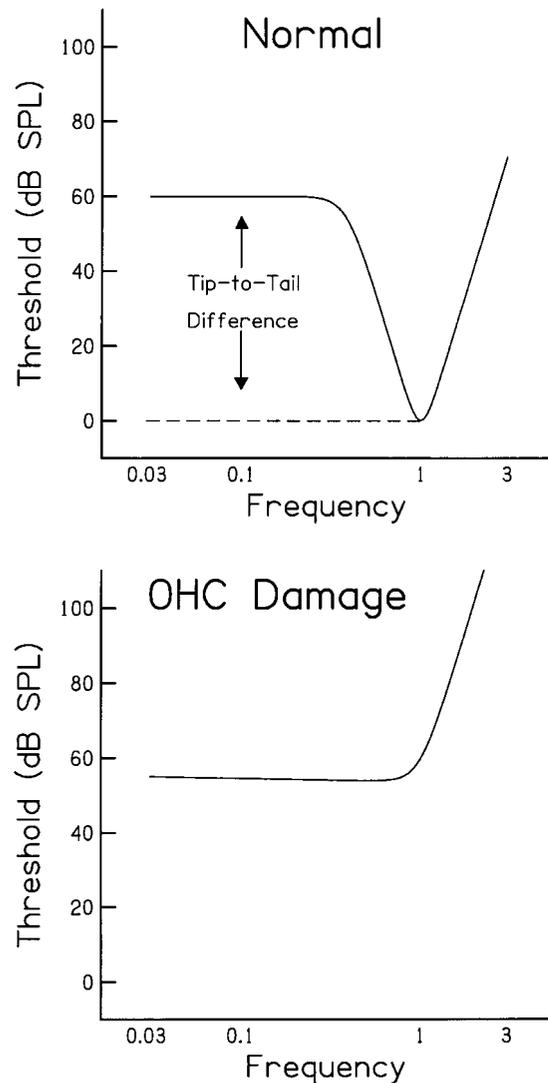


Figure 3. Schematic representations of frequency-threshold curves (FTCs) or tuning curves for individual nerve fibers. Top: An FTC for a fiber innervating a normal cochlear region, with a full complement of outer and inner hair cells. Bottom: An FTC for a fiber innervating a cochlear region where the inner hair cells are normal, but the outer hair cells are absent due to cochlear insult.

cochlea is normal, these low-frequency “tails” of the FTCs are usually observed at thresholds that are about 60 dB less sensitive than thresholds at CF. The magnitude of this difference decreases as threshold elevation increases as a result of damage to the outer hair cells in the cochlea. The difference between thresholds at CF and thresholds on the low-frequency tail is called the tip-to-tail difference. This threshold relationship is one manifestation of upward spread

of cochlear excitation, demonstrating that intense low-frequency stimuli can excite higher frequency (more basal) cochlear regions, but the reverse does not occur. Note that this 60-dB tip-to-tail difference, which is a measure of the maximum frequency selectivity of the cochlea (i.e., when the cochlea is completely normal), is close to the same dB difference between the main energy lobe and the side lobes of a Blackman window. It was on the basis of this normal, maximum difference in tip and tail sensitivity that we originally decided on using Blackman windows for gating tone bursts. While other windowing functions result in greater reductions in side-lobe energy, it makes little sense to select functions that exceed the maximum frequency-resolving capabilities of the cochlea.

Furthermore, it probably makes sense to select stimulus durations that are similar to the travel time of cochlear transients. For example, we can choose the duration of a tone burst as 4 ms divided by the square root of the frequency (Neely, Norton, Gorga and Jesteadt 1988). When the stimulus duration is chosen appropriately, its spectrum is more closely related to short-term responses within the cochlea.

Abnormal Cochlear Frequency Selectivity

With few exceptions, the outer hair cells (OHC) are the most physiologically vulnerable part of the cochlea. When some insult to the cochlea occurs that causes hearing loss, almost invariably, the OHCs are damaged first. As an aside, it is for this reason that otoacoustic emission measurements are useful in UNHS programs. OAEs are generated at the level of the OHCs; if the OHCs are damaged (which is usually the case when hearing loss exists), then OAEs will be reduced or absent. The bottom panel of figure 3 is a schematic representation of an FTC in an ear with OHC damage, resulting in about a 60 dB threshold shift. Note that OHC damage results in greater threshold elevations that occur on the low-frequency tail (compare this FTC to the one shown in the upper panel of figure 3). Stated differently, thresholds are elevated for frequencies at and close to CF, but not for frequencies much lower than CF when only OHC damage exists. Recall that when cochlear function is normal, there is a 60 dB threshold difference between the tip and the tail of the FTC. In the impaired case, that difference is reduced, maybe to 0 dB or even negative, in which case the nerve fiber would be more sensitive

to low-frequency stimuli compared to stimuli at CF (e.g., Liberman and Dodds 1984). Thus, a specific (high-frequency) place with OHC damage might have similar thresholds for low-frequency and CF tones because thresholds changed more for CF tones than they did for low-frequency tones. There is a systematic progression to this relationship in that the threshold at CF will progressively increase as the extent of the OHC damage increases. These features of normal and impaired cochlear frequency selectivity are independent of the stimuli used to elicit a response. They apply equally, regardless of whether clicks, tone bursts, or steady-state tones are used, and they apply, regardless of whether an evoked potential or a behavioral response is being measured.

Even though these cochlear characteristics have general applicability to all auditory stimuli, we will next consider them in relation to the stimuli that are available to elicit an ABR. In the normal case, the (low-level) threshold response to a tone burst is likely derived from the response characteristics of those nerve fibers innervating the place where the nominal center frequency in the stimulus is best represented. At these low levels, energy in the side lobes is less likely to elicit responses because the side-lobe levels may be reduced below the thresholds of fibers that innervate cochlear regions where side-lobe frequencies are represented. As stimulus level increases, however, one would anticipate that the side lobes might be more effective in eliciting responses from those cochlear regions where the frequencies in the side lobes are represented. Thus, a tone burst with broad spectra and complex side-lobe structure would more likely excite a wider range of cochlear places than one with more narrowly defined spectra. Given the differences in side-lobe structure, this will occur at lower levels for linearly-gated tone bursts, compared to tone bursts gated with a Blackman window. Still, in the normal case, the responses elicited by either gating function will likely result in a response coming from the nominal center frequency. This is because thresholds are more equal across frequency and the energy in the main lobe, even for linearly-gated tone bursts, is higher than the energy in the side lobes.

As level increases further, however, it is possible that more distant cochlear regions, even in the normal case, will contribute to the response, both to the side lobes and to the energy in the main lobe if the tone burst is of sufficient level. Cochlear mechanical responses dictate that the spread of excitation is

always from more apical (lower-frequency) regions towards more basal (higher-frequency) regions. The previously described FTCs, in which low- but not high-frequency tails are present, demonstrate this effect.

As hearing loss increases (i.e., as the amount of OHC damage increases), the difference between thresholds at the tip and on the low-frequency tail decreases. Thus, it is possible that a stimulus with a more rich side-lobe structure will excite the low-frequency tails of auditory-nerve fibers having high CFs. Once hearing loss exceeds about 60 dB, however, side-lobe structure will matter less because the cochlea is a less effective frequency analyzer (i.e., for the place with 60 dB of threshold elevation, there is little difference in threshold as a function of frequency, at least for frequencies at and below CF). Under these circumstances, stimulus levels necessary to elicit a response will be such that the low-frequency tails of impaired high-frequency fibers will be reached, and the response is no longer place specific. This is true regardless of the spectrum of the stimulus and the response being measured. Thus, this problem exists both for pure tones and for tone bursts (regardless of the complexity of the windowing function), and it exists for evoked-potential responses as well as for behavioral responses. Pure-tone behavioral thresholds confront the same problems as do ABRs elicited by tone bursts. It does not matter that the stimuli used during pure-tone audiometry have their energy concentrated at a single frequency because of the reduced frequency selectivity of the damaged cochlea.

This reduced frequency resolution also limits the effectiveness of noise masking because thresholds as a function of frequency are more uniform. It becomes difficult to selectively mask basal (high-frequency) cochlear regions so that they cannot respond to lower-frequency tones because of the differential threshold elevation at CF compared to lower frequencies as a consequence of cochlear damage. These concepts are illustrated in figure 4. The top panel shows the FTC when a noise masker, with energy centered at CF, is presented to a normal cochlea (after Kiang and Moxon 1974). Note that the noise shifted thresholds by the same amount (40 dB), regardless of frequency. A tone of 80 dB SPL, which was above threshold in quiet for this nor-

mal high-CF fiber, is now below threshold in the presence of a masker with energy at CF. Thus, direct excitation of this nerve fiber by a low-frequency tone would require 100 dB SPL. In the context of ABR measurements, a masker would effectively eliminate the response of normal, basal, high-frequency fibers, which is the goal when maskers (either high-pass maskers or the high-frequency portion of notched-noise maskers) are used in combination with a tone burst. Under these circumstances, the response to a low-frequency tone is more likely to be coming from

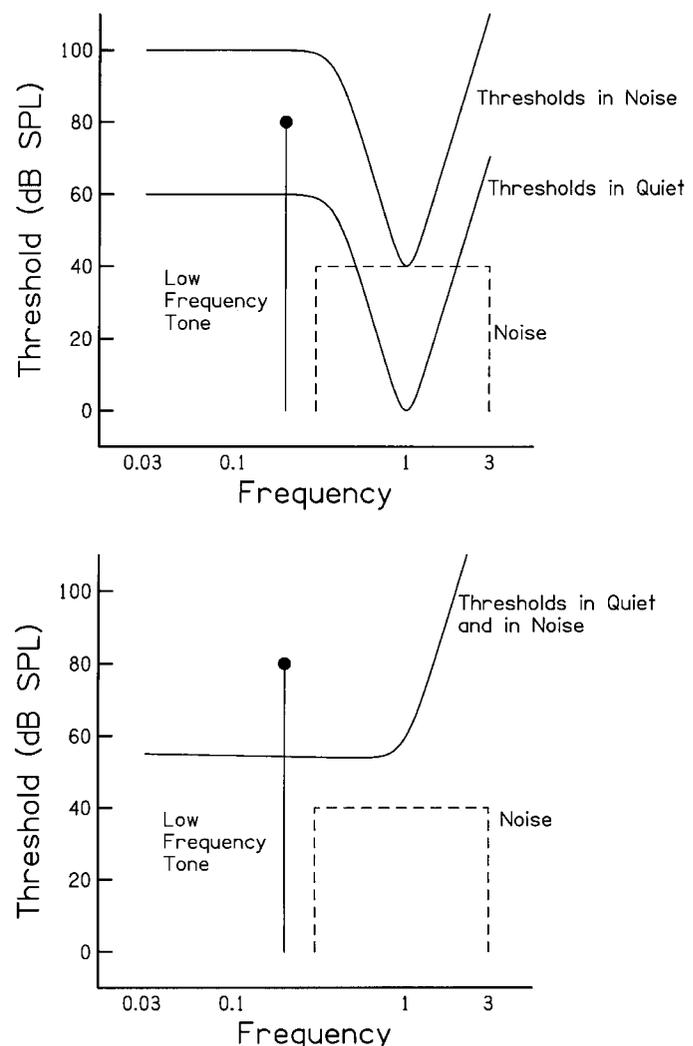


Figure 4. Schematic representation of the effects of “masking” noise on FTCs. Top: Effects of masker when hearing is normal (i.e., both outer and inner hair cells are present and normal). Bottom: Putative effects of masker when hearing loss exists (i.e., outer hair cells are absent, but inner hair cells are completely normal).

the cochlear place where the low-frequency tone is represented. It is unlikely that the response would be coming from high-CF fibers because of the elevation in thresholds on the low-frequency tail of the FTC.

Unfortunately, hearing loss typically is greater in the high frequencies, compared to lower frequencies. That is, it is more likely that hearing loss will be present in the high frequencies, meaning that the FTCs for these impaired, high-frequency regions will be altered as described above. Those conditions are represented in the bottom panel of figure 4. This nerve fiber innervates a high-frequency (basal) cochlear place, and has a threshold of 60 dB SPL at its CF. This is equivalent to what one might expect if the behavioral threshold at this frequency was elevated to 60 dB SPL. Note that thresholds are more similar across frequency, compared to the normal case. There is a 0-dB tip-to-tail difference in the impaired case. When the same noise is presented to this ear as was used to obtain the results in the top panel of figure 4, neither CF nor low-frequency thresholds shift in the presence of the masker. Stated differently, the masker, being below threshold at CF, does not provide any masking, either at CF or for any other frequency along the FTC. Under these circumstances, a low-frequency tone of 60 dB SPL would be at this fiber's threshold, whereas 100 dB SPL was needed in the normal case. Thus, a low-frequency tone at 80 dB SPL would be above threshold, even in the presence of the masker. Returning to ABR measurements, the reduced frequency selectivity of the impaired cochlea makes it difficult to assign a response to any tone burst to a specific cochlear region, and this same reduced frequency selectivity makes it difficult to improve place specificity by introducing maskers that are designed to "occupy" the responses from high-frequency basal fibers. As stated earlier, data exist that suggest that the responses to stimuli with different spectra do not differ in terms of their relative "place" specificity; perhaps this is due to reduced cochlear frequency selectivity, which would affect responses to all stimuli, regardless of their spectral content.

Problems associated with assigning a response to a specific cochlear location exists regardless of the stimuli that are used and the measurements that are made. Thus, these problems exist for pure tones, as well as for linearly-gated and Blackman-gated tone bursts. The problems exist for behavioral measurements as well as for EP measurements (ABR as well as other EP measurements).

One example of a set of circumstances in which spectral definition potentially could influence results is when auditory sensitivity changes rapidly as a function of frequency. As noted above, low-frequency sensorineural hearing loss is one case in which either notched-noise or high-pass noise maskers would help to better define the response because the maskers would shift the thresholds of high CF-fibers to low-frequency stimuli. Maskers would be effective under these circumstances because spread of cochlear excitation is always towards the base. Unfortunately, cases of high-frequency hearing loss with normal or more normal low-frequency hearing are more common. In these cases, excitation of more normal lower frequency fibers, distant from the nominal center frequency, can be accomplished only by direct excitation of these fibers by energy in the stimulus at their CF. These normal low-frequency fibers cannot be excited due to cochlear spread of excitation because the spread is never from high frequencies (represented in the cochlear base) towards lower frequencies (represented in the cochlear apex). Thus, stimuli with spectra that are better defined in the frequency domain are more likely to accurately reflect the magnitude and configuration of hearing loss when high-frequency hearing loss exists.

Summary

In spite of these problems, our interest remains in obtaining an objective measure that correlates with behavioral thresholds. Thus, it remains important to determine the lowest threshold for a specific stimulus, even though the response to that stimulus may not be originating in the cochlear location associated with that frequency in normal ears. ABRs elicited by tone bursts have been shown to provide good estimates of behavioral, pure-tone thresholds. This observation should not be surprising. As stated above, 0 dB HL (re: ANSI 1996) and 0 dB nHL (locally derived for short-duration stimuli) do not share the same reference equivalent threshold levels. However, this effect is restricted to 15–20 dB, and differences between pure-tone and brief-tone thresholds occur mainly for patients with normal hearing. It may be less of an issue in ears with hearing loss, because of their reduced temporal integration. The spectra of the stimuli used to elicit behavioral and ABR responses differ in that pure-tone stimuli have energy concentrated at one frequency, whereas tone bursts have energy centered at the nominal center frequency and

potentially at other frequencies distant from the center frequency. However, the only circumstances under which these spectral differences should affect the agreement between behavioral and electrophysiological measurements is when low-frequency hearing loss exists in the presence of normal high-frequency thresholds. When high-frequency hearing loss exist, which is a more common occurrence, these issues are of less concern as long as the threshold difference between test frequencies does not exceed the level difference between main and side lobes in a gated tone burst. Furthermore, alterations in cochlear frequency selectivity in the presence of hair-cell damage will affect all responses, regardless of whether pure tones or tone bursts are used as the stimuli. Thus, one should be able to predict behavioral thresholds from ABR thresholds because the representation of both pure-tone stimuli and gated sinusoids are affected in the same way, especially in cases in which moderate or greater hearing loss exists. This bodes well for the use of tone-burst ABRs thresholds as a guide in the selection of amplification using algorithms that are based on pure-tone thresholds.

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