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□ Original Article □

Time-Intensity Relations in Bekesy Audiometry

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Threshold and amplitude measurements were made for fixed frequency Bekesy pure tones on subjects with normal hearing, sensorineural hearing impairment, and functional hearing loss. Following conventional Bekesy audiometry (intensity change 4 dB/sec), −20 dB was added to a signal at the threshold of audibility (bottom of the spike). When sensation was lost at the threshold of inaudibility (top of the spike), +20 dB was added. Adding ±20 dB in subjects with normal hearing reduced the amplitude of the spike about 4 dB, corresponding to 1 second, for both pulsed and continuous tones. Adding ±40 dB produced essentially similar findings. Adding ±20 dB in subjects with sensorineural loss with reduced amplitude of continuous tone tracings also reduced the amplitude approximately 4 dB for pulsed tones, but 3 dB, corresponding to 0.75 seconds, for continuous. tones. Abnormal rapid adaptation may account for this reduced amplitude of the spikes. A subject with multiple sclerosis producing excessive abnormal adaptation showed spectacular increased amplitude for continuous tone only when −20 dB was added at bottoms and +20 dB at tops of spikes. An explanation based on slow adaptation is offered. Subjects with functional hearing loss may emphasize either time or intensity in their inappropriate responses when ±20 dB is added at tops and/or bottoms of spikes.

Key Words: Threshold and amplitude, add ±20 dB, abnormal adaptation, functional hearing loss.

Sensation depends on both spatial and temporal stimulation. These can be supplementary, but at times one may dominate or even replace the other. For example, a high pitched tone (spatial stimulation of the basilar membrane) interrupted at a lower frequency gives a sensation of the lower frequency (temporal summation). Onset and decay time and adaptation cause significant differences between physical stimulus and corresponding sensation. Bekesy tracings by the usual method of limits record the onset and cessation of hearing. All down strokes, while intensity is increasing, represent periods of no hearing. Up strokes record continuous hearing as intensity is decreasing. When the physical stimulus is decreasing steadily during the upstroke, threshold sensation is subjectively essentially uniform between the onset and end of hearing.

Bekesy spikes are usually described by the vertical amplitude or dB difference between tops and bottoms. Amplitude is the vertical side of a right triangle with hypotenuse the tracings, and base the time between adjacent tops and bottoms . For a given attenuation rate and paper speed, the slope of the tracing (tangent of angle$=\frac{\text{amplitude in dB}}{\text{time in seconds}}$) is constant for both hearing and non-hearing limbs. Bottoms of spikes indicate the (ascending) threshold of audibility and tops the (descending) threshold of inaudibility.

A crude experiment demonstrates that time is a significant component of the Bekesy record. If, during a fixed frequency tracing on a Bekesy audiometer, the operator rapidly lifts the recording pen 20 or more dB at the moment of pen reversal at the bottom of a spike, the output is reduced accordingly. Physical intensity is manifestly inadequate to account for the hearing sensation which continues for a considerable time. The relative contribution of time and intensity components when a large abrupt physical change is superimposed on the sliding Bekesy stimulus at the onset and end of hearing sensation is the subject of this pilot experiment.

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SUBJECTS

There were 9 subjects with bilateral normal hearing, 7 patients with unilateral sensorineural loss without abnormal adaptation, 1 with unilateral sensorineural loss and marked abnormal adaptation, and 2 with functional hearing loss.

INSTRUMENTATION

To precisely measure the time factor after abruptly reducing the stimulus intensity in Bekesy tracing, the signal from a sine wave generator was passed through an operator controlled amplifier to a Grason-Stadler E3262A recording attenuator controlled by the subject. Pressing the subject's button decreased the intensity; releasing increased the intensity. At the option of the operator, pressing or releasing the button could simultaneously introduce ±20 dB of additional attenuation. An optional ±40 dB attenuation device was also available. Rise and decay times were 5 msec to prevent click cues.

When −20 dB or −40 dB is added to a signal at the threshold of audibility (bottom of spike), the stimulus intensity abruptly falls well below threshold. Any continuing sensation can no longer be attributed to intensity. When the subject's tone sensation has vanished and he marks the threshold of inaudibility (top of spike), +20 dB is added automatically, thus the previous −20 dB is neutralized. The signal remains inaudible until intensity again reaches the threshold of audibility level. If this sequence is repeated, all upstrokes represent sensation without corresponding stimulus intensity; downstrokes indicate periods of no hearing until intensity increases to the threshold of audibility.

PROCEDURE

Fixed frequency tracings with an attenuation rate of4 dB/sec in 0.2 dB steps were obtained for both pulsed and continuous tones. Pulsed tones were interrupted 2.5 times per second with a duty cycle of 50%. Thus, on- and off-times were 200 msec. Normal subjects were tested at 1000 Hz and patients at frequencies with hearing loss. The middle 45 seconds of each 60 second tracing were analyzed. Amplitude was the mean difference in dB between top and bottom of each spike. The opposite ear was masked by white noise at 80 dB SPL in patients to eliminate the possibility of cross-hearing without cross-masking.

RESULTS

In Figs. 1-4, the spike amplitudes and corresponding times obtained by adding −20 dB at bottoms and +20 dB at tops of spikes is the ordinate. The abscissa is the amplitude of the spikes and corresponding time by conventional Bekesy audiometry with the same subject and equipment. A straight line to best fit the data points shows this relationship.

Adding ±20 dB in nine normal subjects reduced the median amplitude by about 4 dB and the stroke

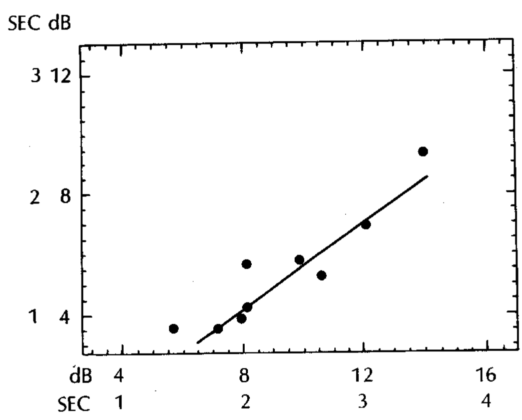

Fig. 1. Normal hearing subjects. Pulsed 1000 Hz tones. In Figs. 1-4, the abscissa represents the amplitudes of the spikes and the corresponding times measured by conventional Bekesy audiometry. The ordinate denotes the amplitude of the spikes and corresponding time obtained by subtracting 20 dB, when the subject just marks that he hears the tones, and adding 20 dB, when the subject just marks that he no longer perceives the tone, i.e., at the bottoms and at the tops of the spikes, respectively.

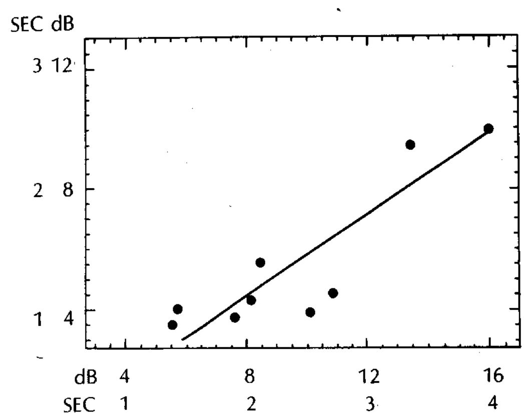

Fig. 2. Normals. Continuous 1000 Hz tones.

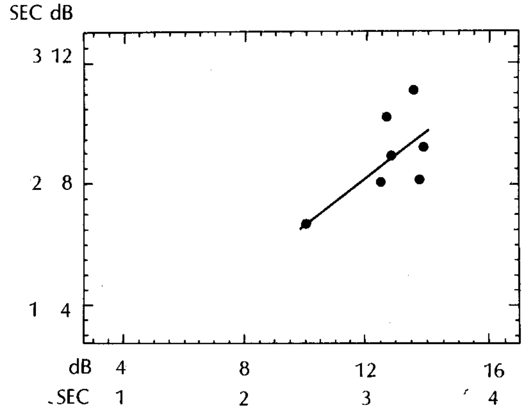

Fig. 3. Sensorineural hearing loss. Pulsed tone at frequencies with hearing loss.

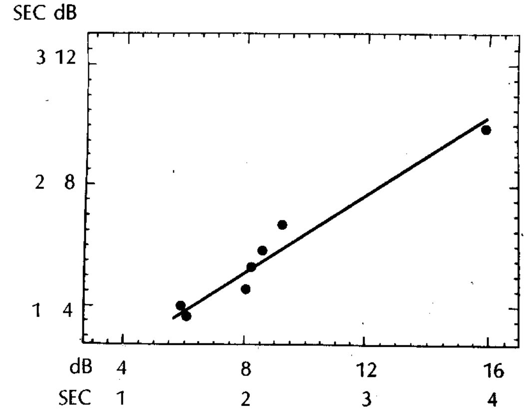

Fig. 4. Sensorineural hearing loss. Continuous tone at frequencies with hearing loss.

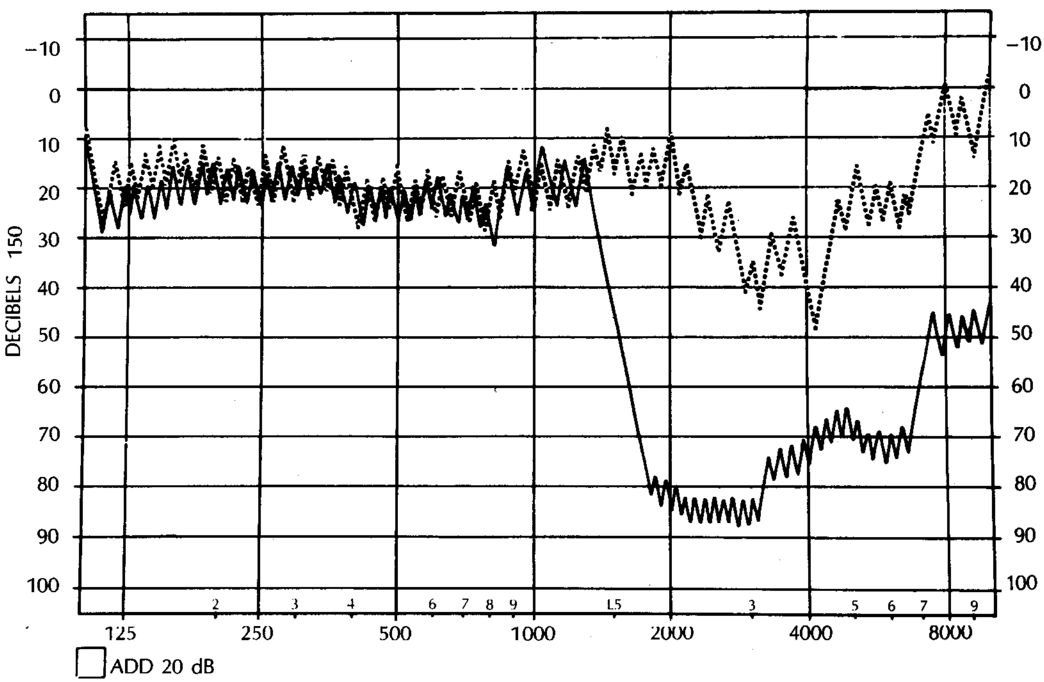

Fig. 5. Sensorineural hearing loss with marked high frequency abnormal adaptation. Continuously variable Bekesy threshold tracings (Grason-Stadler E 800) with an attenuation rate of 5 dB/sec. Broken lines represent pulsed tone; solid lines, continuous tone.

time by one second for both pulsed and continuous tones, irrespective of amplitude differences in the tracings among subjects (Figs. 1 and 2). In seven subjects with sensorineural hearing loss characterized by reduced amplitude of continuous tones only, pulsed tone median amplitudes were also reduced by about 4 dB or one second (Figs. 3 and 4). Continuous tone median amplitude tracings were reduced by about 3 dB or 0.75 seconds. Adding +40 dB produced essentially similar findings.

Continuously variable frequency tracings with a 5 dB/sec attenuation rate on a Grason-Stadler E 800

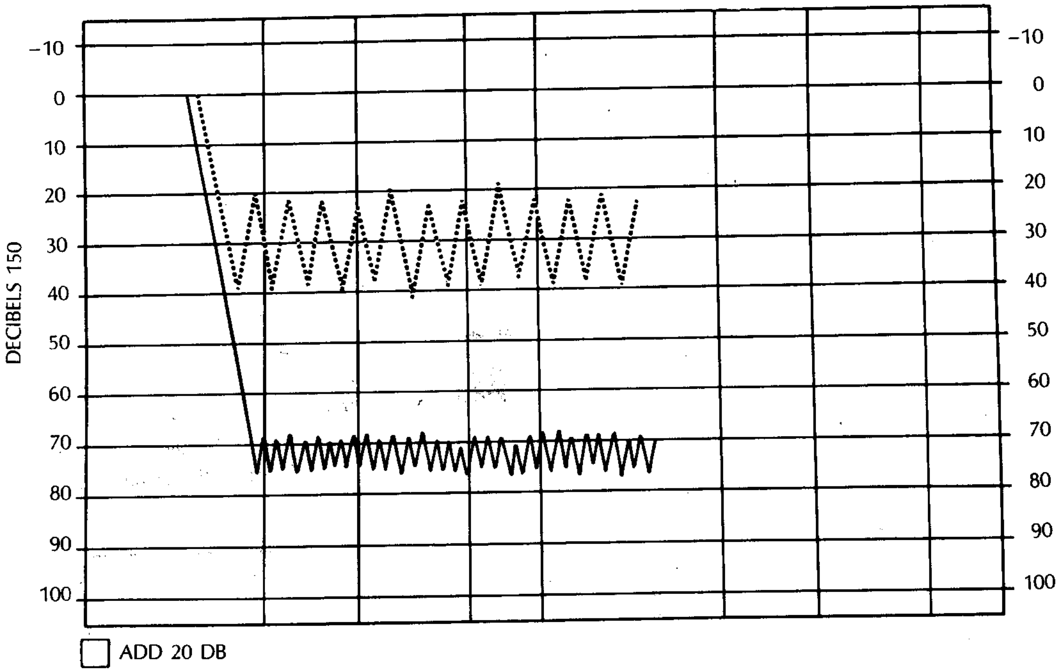

Fig. 6. Fixed frequency tracings at 4000 Hz for the same subject in Fig. 5.

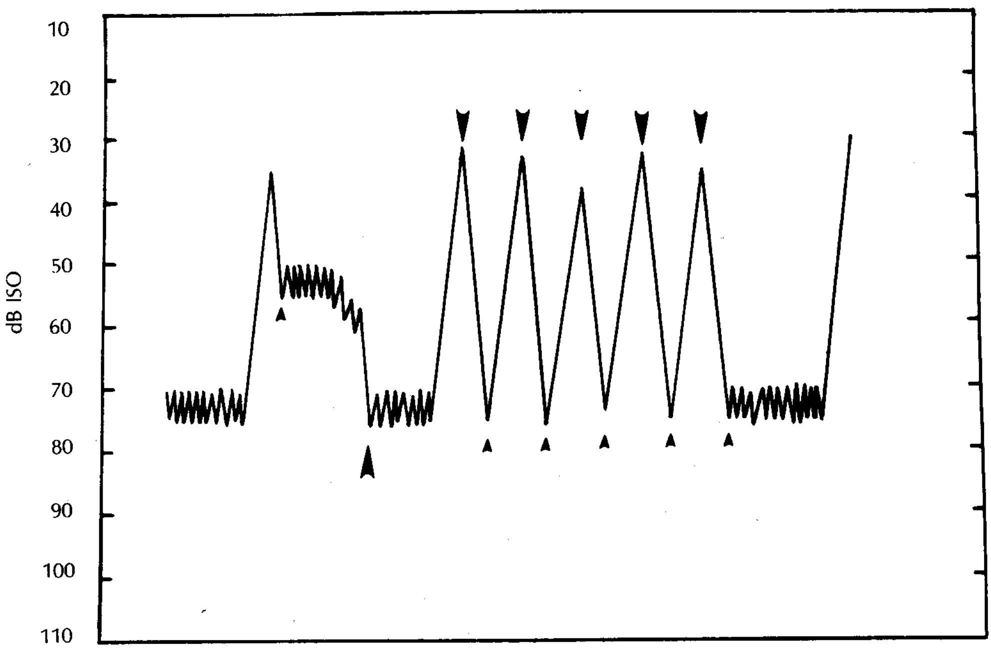

Fig. 7. Continuous tone fixed frequency tracings at 4000 Hz with an attenuation rate of 4 dB/sec for the same subject as in Fig.5. In this Figure and Figures 8 and 9, large arrows indicate the adding of intensity +20 dB at those points; small arrows indicate the adding of −20 dB at those points. Tracings are recorded from right to left by a Grason-Stadler E 3262A recording attenuator.

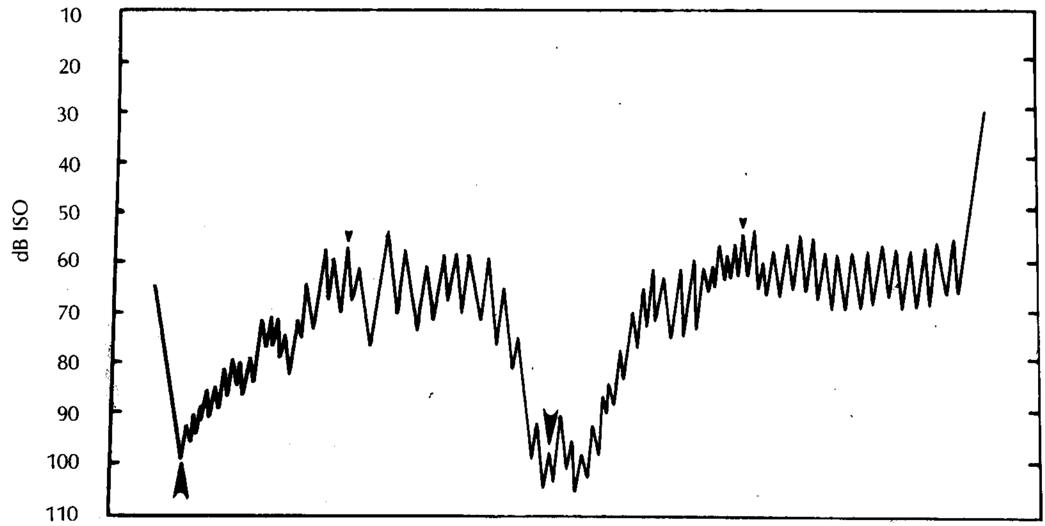

Fig. 8. Continuous tone fixed frequency tracings in a subject with functional hearing loss.

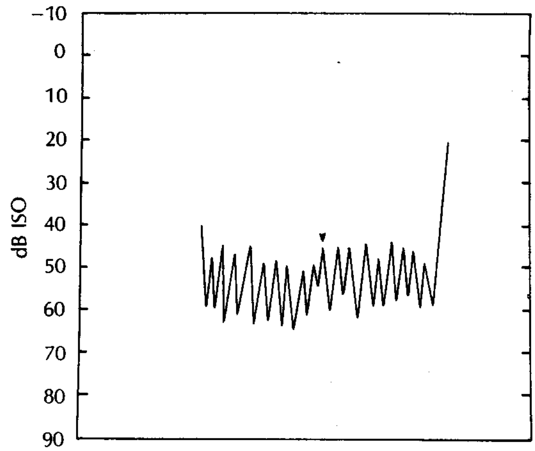

Fig. 9. Continuous tone fixed frequency tracings in another subject with functional hearing loss.

Bekesy audiometer were performed on a subject with multiple sclerosis. These showed wide separation between normal amplitude pulsed and reduced amplitude continuous tone tracings at frequencies above 1500 Hz (Fig. 5). In fixed frequency tracings at 4000 Hz, there was a 35 dB separation between about 15 dB amplitude pulsed and 5 dB amplitude continuous tone thresholds of audibility at the bottoms of spikes (Fig. 6). Reduction of amplitude similar to normals occurred in fixed frequency 4000 HZ pulsed tone tracings with ±20 dB. This was also true for both pulsed and continuous tones at random frequencies below 1500 Hz and in the opposite normal ear. Fig. 7 records this patient's ±20 dB fixed frequency tracings by a 4 dB/sec attenuation rate for 4000 Hz continuous tone on a Grason-Stadler E 3262 recording attenuator. In Figs. 7, 8 and 9 the tracings are from right to left. All descending strokes represent no hearing; rising strokes, continuous hearing. Figures 8 and 9 are examples of functional hearing loss.

DISCUSSION

In the standard Bekesy method of limits, an inaudible slowly increasing stimulus approaches a level where summation of subliminal stimuli is possible. The potential stimulating effect of increasing intensity may be reduced by concurrent adaptation which may occur even with inaudible stimuli when the increase is slow (Harbert and Young 1962). At some point, stimulative forces overcome restorative and all or none action currents are triggered to initiate conscious sensation. At the moment of perception, the subject presses a button to both signal this event and reverse attenuation. During the reaction time between onset of perception and mechanical activation of the switch, there is an increase of intensity. Finger withdrawal reaction time for tones of 50 dB SPL is about 280 msec (Goldman *et al* 1981). As intensity of an acoustic stimulus decreases, reaction time increases (Chocholle 1954). If finger withdrawal and pressing or releasing a button are similar tasks, reaction time at the threshold should be at least 300 msec, equivalent to 2.2 dB for an attenuation rate of 4 dB/sec at each end of the spike. The bottom part of the hearing spike is at suprathreshold intensity while the top part represents false hearing because of reaction time.

Bekesy threshold sensation does not follow the physical envelope of slowly decreasing intensity as in suprathreshold hearing. Subjectively, there is no significant loudness difference between the onset and termination of threshold hearing for clinical attenuation rates of 2-5 dB/sec. When intensity is no longer capable of eliciting axonal responses, hearing continues during the ensuing decay time. During decay, a value is finally reached which cannot be distinguished from a complete switching off of the tone. Shorter decay times than 0.3 sec are indistinguishable from physiologic decay time (Bekesy 1960). At the end of the physical stimulus there is at least a 300 msec physiological decay time and 300 msec reaction time to activate the switch signaling the threshold of inaudibility. This minimum 600 msec (2.4 dB for 4 dB/sec of attenuation rate) has no relation to intensity. Doubling the attenuation rate increases the amplitude by a ratio of 1 to 1.5 (Harbert and Young 1962).

When attenuation is reversed at the top of a spike, intensity is about 2.4 dB below the threshold of inaudibility because of the 300 msec decay and 300 msec reaction time. There is no hearing until intensity, reduced by concurrent adaptation, increases to the suprathreshold level where physiologic onset time is possible. For suprathreshold intensities, onset time is 0.7 seconds.

More time should be required for a slowly increasing tone with concurrent adaptation to initiate all or none responses. This may further increase the threshold of audibility raised by reaction time. Faster attenuation rates should increase this recorded threshold. The suprathreshold intensity at the bottom of a spike is not subjectively louder than later because full loudness appreciation requires 180 msec for moderate loudness and probably 300 msec for threshold (Bekesy 1960). This requirement and about a 25 msec physical rise time may account for the fairly uniform threshold sensation. During attenuation, there is recovery from adaptation which also keeps the sensation level and affects the threshold of inaudibility when abnormal (Fig. 7).

The role of acoustic stimulation may be determined by measuring residual hearing when the acoustic stimulus is completely removed at the onset of hearing. Removal of acoustic stimuli by adding −20 dB stops the input of neurones firing at slightly suprathreshold levels because of perception and reaction times as previously noted. Decay time starts immediately. With normal presentation there is a period of suprathreshold hearing because of reaction time, followed by threshold and infrathreshold hearing because less input is required to initiate than to maintain firings. During attenuation there is also recovery from adaptation. This portion, represented by 4 dB or 1 sec, is related to the period between onset and cessation of action potentials provoked by acoustic stimuli. There is decay and reaction time at the end of physical hearing in both ±20 dB standard presentations. Further tests with different attenuation rates will determine the relative importance of time and intensity for this physical hearing period. Its constancy for a given attenuation rate is in contrast with the wide variations of the sum of other parameters constituting the Bekesy spike.

In Fig. 7, as intensity of the inaudible continuous tone decreases from 30 dB on the right, there is concurrent abnormal adaptation starting immediately because intensity is in the audible range for pulsed tones (20-40 dB in Fig. 6). There is no hearing because the rate and depth of adaptation are greater than the intensity increase by the attenuator until a threshold of equilibrium is reached between 75 dB and 70 dB. After eleven spikes, −20 dB is added at the bottom of a spike producing a sudden change of intensity to 55 dB. While some slow adaptation may persist, recovery from rapid adaptation is immediate and complete within 30 milliseconds (Harris 1969). Hearing continues because recovery from both slow and rapid adaptation is faster and more effective than intensity decrease until chart level 35 dB (actual 15 dB) is reached. This corresponds to a threshold of inaudibility of 20 dB for pulsed tone in Fig. 6.

When hearing is lost at the top of the spike, the addition of +20 dB increases the level to 35 dB which is still below the threshold of audibility even for pulsed tones (40 dB in Fig. 6). As intensity increases, concurrent abnormal adaptation again prevents hearing before the adapted threshold of audibility at 75 dB and −20 dB is added again. When, after four similar sequences, −20 dB is not added, the threshold of equilibrium between 75 and 70 dB is again retraced. Dwell time at the threshold of equilibrium prior to adding −20 dB does not affect the threshold because it is the same whether −20 dB is added after the first or eleventh spike.

Adding +20 dB at the bottom of a spike produced a new starting intensity of 95 dB. Hearing continued to 58 dB chart level (actual 78 dB). The threshold of inaudibility now drifted to equilibrium at 50 dB (actual 70 dB) where the threshold of equilibrium between 50 dB and 55 dB (actual 70 dB and 75 dB) was traced repeatedly. When −20 dB was added at 55 dB chart (actual 75 dB), hearing continued to 35 dB chart and actual levels. The top of the spike at 35 dB represents the first spike from a starting intensity of 95 dB with an intervening period of thresholds of equilibrium between 75 dB (chart 55-50 dB) but without interruption. The first spike was really at 58 dB (actual 78 dB) with threshold drift to 50 dB (actual 70 dB) and equilibrium between 70 and 75 dB for a while before resuming recovery when −20 dB was added. This is obviously slow adaptation.

When −20 dB was added to the first series of 75 dB for attenuation rates of 5 dB/sec. High suprathresh-first presentation of 75 dB or after a prolónged threshold of equilibrium. It is untenable to ignore the 75 dB starting intensity and consider that adding −20 dB is the same as a new 55 dB starting intensity. The last time −20 dB was added to a threshold of equilibrium at 75-70 dB (chart 55-50 dB), the first and only spike occurred at 35 dB (chart and actual). The last 55 dB starting intensity differed from the first one in that the first one was recovery from 75 dB while the last was from 95 dB. In both instances, the first threshold of inaudibility was 60 dB above the highest starting intensity.

In a case of severe slow adaptation, the conventional audiometric threshold was 55 dB. The first spike was at 60 dB for Bekesy pulsed tone followed by 35 dB threshold drift to equilibrium. Steady tone was never heard within the limits of the audiometer (120 dB on Grason-Stadler E800) (Harbert and Young 1962). Normally, every 20 dB increase in suprathreshold starting intensity raises the threshold of the first spike 1.5 dB for attenuation rates of 5 dB/sec. High suprathreshold starting intensity has a much more profound effect in abnormally adapting ears and may even affect pulsed tones (Harbert and Young 1962; 1968).

The addition of ±20 dB at tops and/or bottoms of spikes may tax the ingenuity of malingerers or the ability to respond by those with other functional disorders. To minimize the possibility of abnormal adaptation, only pulsed tones should be used. When −20 dB is added to bottoms and +20 dB to tops after a sample threshold and amplitude are established, the ensuing tracing should have the same threshold of audibility and a consistently higher threshold of inaudibility, i.e., hearing without intensity.

If actual hearing is well above the traced threshold, the subject would notice a large decrease in intensity to which he would respond with an immediate or delayed reaction time. For a true threshold, there should be no immediate response. A delayed reaction might be construed as a proper reduced amplitude spike. If +20 dB is then added, the original loudness returns and he could try to straddle the area between plus and minus 20 dB. This would be difficult on an intensity criterion but could succeed if previously established rhythm is the guide. Erratic presentation of plus and minus tax the subject's intensity criterion.

If −20 dB is added at the bottom of a spike and +20 dB is not added at the top, there should be a single reduced amplitude spike followed by a continuous period of no hearing to a 20 dB higher threshold of audibility. Adding +20 dB at the bottom of a spike should record continuous hearing to a threshold of inaudibility 20 dB lower. Because of previously established rhythm, naive listeners may record a series of spikes instead of a straight line up or down when 20 dB is either added or subtracted at the bottom of a spike. During the fluctuations between an alleged threshold of audibility and inaudibility, the new threshold may be too high or low because of impairment of the subject's spurious threshold criteria. Some subjects may emphasize time between button pressings and fail to adjust to changed intensity.

In Fig. 8, starting at 30 dB on the right, a baseline threshold was established between about 55 and 65 dB. Adding −20 dB produced no change in rhythm as he traced a series of increasing intensity spikes terminating in a new threshold between 95 dB and 105 dB, a 40 dB instead of 20 dB higher level. There should have been a single amplitude spike followed by a straight line representing constant absence of hearing to a threshold between 75 dB and 85 dB. When +20 dB was added, there should have been a straight line of continuous hearing to the original level. Instead, he alleged interrupted hearing to the approximate original level. The next −20 dB addition produced erratic spikes to 100 dB where 120 dB was added. Now he recorded a correct straight line to the end of the chart. While he tried to adjust to rapid intensity changes, spurious original rhythm was maintained. Adjustment to his subjective intensity threshold was more precise from a higher intensity and the second response was correct.

In Fig. 9, adding −20 dB produced threshold drift less than 10 dB higher and then a drift back to practically the original chart level. Only time between button pressing rather than intensity apparently governed this tracing.

SUMMARY

1. For a 4 dB/sec attenuation rate, only about 4 dB

or 1 second of normal excursion could be attributed to physical intensity. The intensity (time) portion was a constant part of normal amplitude variations for both continuous and pulsed tones. This period represents response to acoustic stimulation between onset of hearing and cessation of acoustic effects, probably action currents as modified by concurrent release from adaptation. The Bekesy method is also subject to variables common to all psychophysical measurements, such as attenuation, motivation, instructions, etc.

2. In a pilot group of subjects with sensorineural hearing loss characterized by reduced amplitude continuous tone tracings, physical intensity hearing time was also 4 dB or 1 second for pulsed tone but 3 dB or 0.75 seconds for continuous tone. Abnormal rapid adaptation may account for this reduced intensity time.
3. A subject with multiple sclerosis had spectacular increased amplitude excursions in the range of hearing loss for continuous tone presentation only when −20 dB was added at bottoms and +20 dB at tops of spikes. Continuous tones in the normal hearing range and pulsed tones in the hearing loss area produced normal reduced amplitude tracings. An explanation based on normal rapid recovery from abnormal adaptation rather than decrease of intensity by the attenuator is suggested.
4. Subjects with functional hearing loss may emphasize either time (rhythm) or intensity in their inappropriate responses, when ±20 dB are added at tops and/or bottoms of spikes. One subject demonstrated both.

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