SELF-TESTING AUTOMATIC-RECORDING AUDIOMETRY: AN APPRAISAL

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Introduction

RECENTLY, there has been an increase in the number of conflicting reports on the reliability and value of self-recording audiometry. It is therefore considered opportune to set down some of the facts, based upon experience in this field.

Historical

Self-recording audiometry was introduced by Békésy in 1947.

Description of Test

Békésy's original instrument used a continuous test tone, the intensity of which was controlled by a motor driven attenuator, giving an increase or decrease of intensity at a constant rate. The patient was instructed to depress a key when nothing was heard. At the start of the cycle of operations, an audible tone was presented which diminished steadily to inaudibility. As soon as this condition was reached, depression of the key reversed the direction of the attenuator so increasing the intensity, when the threshold was again crossed. Release of the key would initiate another reversal, so that the threshold was crossed repeatedly. A graphic record of threshold against time shows oscillations about a mean. At the same time, the frequency of the test tone was continually changed so that the desired range of frequency was covered. The graphic record was therefore one of threshold against frequency. This audiometric method can therefore be defined as measurement of the threshold of perception for hearing as a continuous function of frequency using a continuous stimulus and employing the classical psycho-physical procedure of the method of adjustment, with an automatic continuously-recorded tracking technique. It is essentially a cyclical process incorporating negative feed-back, the subject acting as a discontinuous control element in the loop (Oldfield, 1955). Various modifications may be introduced into this audiometric method. Thus, as was done by Békésy himself, the frequency of the test tone can be kept constant to provide a continuous recording of the threshold as a function of time only. The stimulus may also be periodically interrupted

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to give a pulsed test-tone. Moreover, instead of the stimulus gradually changing as a function of both intensity and frequency, one second test tones may change in 5 dB or 10 dB steps and test at certain selected frequencies only, with punch-card recording of the threshold. This modification is encountered in the U.S.A.F. School of Aviation Medicine Automatic Audiometer (Brogan, 1956). Such audiometers no longer employ the psycho-physical procedure of the method of adjustment but that of the method of gradual limits. The Rudmose Associates Model ARJ-3 Automatic Audiometer (McMurray and Rudmose, 1956) also tests at discrete frequencies, but still employs the method of adjustment, with the continuous test tone changing in 2·5 dB steps.

Thus the only common basis to all these developments of the original audiometry devised by Békésy is that the person is self-tested and the audiogram is automatically recorded. In this paper, however, we shall be primarily concerned with continuously recorded audiometry employing the psycho-physical procedure of the method of adjustment.

Uses

In clinical audiology, Békésy-type audiometry is used for the following purposes:

(1) Measurement of the threshold of hearing;
(2) To provide an index of the presence of the loudness recruitment phenomenon;
(3) To detect and measure abnormal auditory adaptation;
(4) To provide a measure of temporary hearing loss, in the belief that this has some relation to susceptibility to permanent hearing loss due to intense noise.

In attempting to assess the merits of any test such as this, it is relevant to consider the validity, reliability, distribution of the norm, advantages, disadvantages, indications and contra-indications. The four uses of Békésy audiometry will therefore be discussed along these lines.

I. Measurement of the Threshold of Hearing

Validity

The validity of Békésy-type audiometry using a continuous tone has been investigated by comparing the threshold measured by this method with that measured by conventional individual pure tone audiometry operating in 2 dB steps (Burns and Hinchcliffe, 1957). Except at 1,000 c/s, there was no significant difference between the two thresholds. The difference at 1,000 c/s was attributed to starting the individual pure tone audiometry at this frequency and not checking the threshold at this frequency when the thresholds at the other frequencies had been measured. It was concluded that measurement of the auditory threshold by the

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two methods gave essentially the same result. This validation of Békésy-type audiometry, however, was obtained using a continuous stimulus and a sample that was predominantly normal.

The experimental work of Rosenblith and Miller (1949) and of Garner (1947) indicates that there may be an appreciable difference between auditory thresholds determined using a continuous test tone and those determined using an interrupted test tone. However, Palva (1956a) measured thresholds of hearing with a Békésy-type audiometer using both continuous and interrupted test tones. He showed that for frequencies ranging from 250 c/s to 4,000 c/s there was no significant difference between the thresholds measured by these two methods when the repetition rate for the interrupted tone was 120/min. and the duty cycle (=duration of test tone/total duration of cycle) was 0·5. It would thus appear that, when the stimulus is pulsed in this manner, the measured threshold is not essentially different from that determined by a continuous tone.

It may be argued that the occurrence of the phenomenon of threshold drift, or abnormal per-stimulatory adaptation (v. infra), will invalidate Békésy-type audiometry as a method of measuring the threshold, especially if, as McLay (1959) claims, this drift may account for a discrepancy of as much as 60 dB. However, this type of result is encountered only in some cases of perceptive type deafness and even then is not common (Palva, 1958a). Thus, instead of detracting from the value of Békésy-type audiometry in both screening and diagnostic tests, the possible occurrence of this phenomenon of threshold drift actually adds to it. In screening audiometry, we attempt to pick out people with hearing defects in a group of predominantly normally hearing individuals. The occurrence of abnormal per-stimulatory adaptation at threshold will help to accentuate particular cases of subnormal hearing, rendering detection and separation easier. In diagnostic audiometry, we are offered an additional test, albeit as yet of uncertain significance, in our armamentarium.

Reliability

The test-retest reliability, i.e. the repeatability, of Békésy-type audiometry, along with that of conventional audiometry employing the method of limits has also been investigated (Burns and Hinchcliffe, 1957). The product-moment correlation coefficients for the frequencies 500 c/s to 6,000 c/s is shown in Fig. 1. The results show that Békésy-type audiometry is as reliable as conventional pure tone audiometry.

Van der Waal and van Dishoek (1955) investigated the accuracy of Békésy-type audiometry as compared with conventional audiometry by considering the size of the standard deviation of three threshold measurements in each of ten people of normal hearing and in each of ten deaf people. In each series, the average standard deviation for conventional audiometry was significantly larger than that for Békésy-type audiometry

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at each frequency measured. Moreover, the average standard deviation at sixteen different frequencies of a continuously-recorded threshold showed no significant difference between a group of eight conductively deaf ears and nine perceptively deaf ears. Since threshold drift is a function of perceptively deaf ears only, we can conclude that the occurrence of this phenomenon does not influence the general reliability of Békésy-type audiometry. It is assumed, of course, that van der Waal and van Dishoek's samples were representative of the perceptively deaf population.

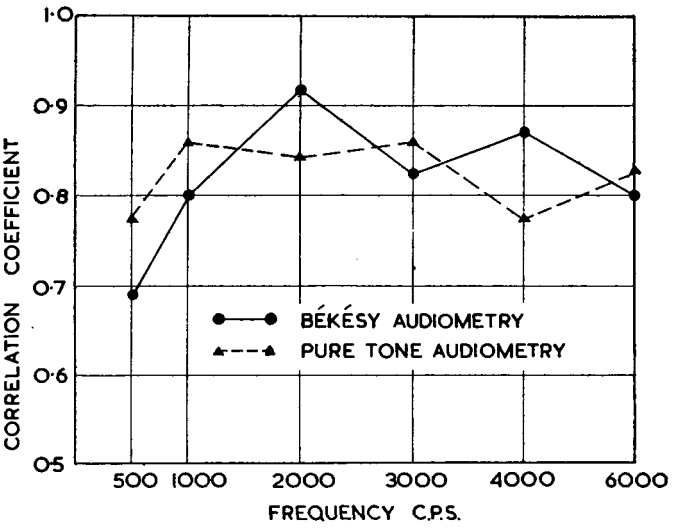


FIG. 1.
Test-retest reliabilities for Békésy audiometry compared with conventional pure tone audiometry. (After Burns and Hinchliffe, 1957.)

Distribution of the norm

Since Békésy-type audiometry effectively measures the same threshold as conventional clinical audiometry, and does so as reliably, the same norms may be applied in the interpretation of thresholds obtained by this procedure. Using conventional audiometry, we have already determined the distribution of thresholds of hearing as a function of frequency and of age on a random sample population (Hinchcliffe, 1959). Interpolation of these results can give the necessary data for any frequency determined by continuously recorded audiometry.

Advantages

Determination of the auditory threshold by Békésy-type audiometry provides information at all frequencies instead of merely at selected frequencies as is the case with conventional audiometry. The automatically-registered graphic record of the threshold also eliminates experimenter error.

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Self-Testing Automatic-Recording Audiometry

Since Békésy-type audiometry uses an effectively continuous intensity scale in contrast to the 5 dB. steps of conventional clinical audiometry, the standard deviation of the mean of a number of measured thresholds on a given individual will be smaller. Consequently the progress or regression of a hearing defect, or even the emergence of one, is detectable at an earlier stage by using a Békésy-type audiometry. Significant changes in the auditory threshold at a given frequency can be calculated from van der Waal and van Dishoek's (1955) data. For a Békésy audiogram, it is 3 dB. at 1,000 c/s, 4 dB. at 2,000 c/s, 5 dB. at 4,000 c/s, 6 dB. at 125 c/s, 250 c/s, 500 c/s and 4,000 c/s and 7 dB. at 8,000 c/s. This compares favourably with 10 dB. (i.e. 2 steps of 5 dB.) at any of these frequencies for the conventional pure tone audiogram.

Disadvantages

It is frequently stated that a threshold determined by Békésy-type audiometry takes longer to measure. However, the frequency sweep can always be speeded up. No "speeding-up" can be applied to conventional clinical audiometry.

Since the instrument is more complicated than the clinical pure tone audiometer, it could be argued that potentialities for defect are greater and that some additional maintenance for the mechanical part of the instrument may be necessary.

Indications

Dishoek (1956) maintains that the early detection and exact registration of an acoustic trauma is only possible by Békésy-type audiometry. The use of this type of audiometry may therefore confer certain advantages in hearing conservation programmes where there is large-scale examination of personnel subjected to acoustic hazards.

Contra-indications

It is possible that a small proportion of people may find the technique of Békésy audiometry inherently difficult. But experience has shown that the number of wasted audiograms over many thousands of examinations is very low. It would be interesting to speculate on whether these people might have difficulty with conventional audiometry also.

II. Indication of Loudness Recruitment

Békésy (1947) noticed that small excursions in the continuously-recorded audiogram are associated with an ear showing the loudness recruitment phenomenon.

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Validity

Palva (1956b) examined a series of 39 patients belonging to various diagnostic categories, and tested them by both continuously-recording audiometry and the Fowler (1928) alternate loudness balance test. Analysis of his results for the simultaneous occurrence of both complete asymptotic loudness recruitment and an amplitude of excursion of the auditory threshold of 5 dB. or less at any frequency in the Békésy technique shows a coefficient of association of nearly 0·99. If we restrict ourselves to consideration of the amplitude at a frequency of 2,000 c/s or more, then an even better correlation obtains. In addition, Palva (1957) subsequently pointed out that, at low frequencies, one cannot predict the loudness function on the basis of the threshold tracings. Although Palva's (1956b) investigation used continuously-recording audiometry as a single function of time instead of as a function of frequency also, he points out that the majority of cases show unaltered amplitude of excursions as a function of time. We can therefore conclude that, for frequencies above 2,000 c/s, a small amplitude of excursion of the continuously-recorded auditory threshold is a valid test for complete, asymptotic loudness recruitment.

For the reasons that Palva (1958a) has given, cases of linear recruitment seldom, and of delayed recruitment never, show a small amplitude of the continuously-recorded threshold excursions. We have inadequate data on the correlation of incomplete loudness recruitment and the amplitude of the excursions of continuously-recorded thresholds, but inspection of McLay's (1959) recent data shows that one case (perceptive deafness) with incomplete asymptotic recruitment and one case (acoustic neuroma) with incomplete linear recruitment showed no significant reduction of the amplitude of the continually-recorded threshold. This discrepancy cannot be brushed aside by claiming that loudness recruitment is only considered to have occurred if recruitment is complete. Loudness recruitment is defined as the increase in loudness of tones more rapidly than normal when the growth of loudness is related to logarithmic increments of the stimulus intensity above the threshold (Hirsh, 1952). Recruitment may therefore be complete or incomplete. The difference between these two types may, in some cases, be due to the arbitrary fixation of the upper limit on the audiometer as 100 dB. (or less) with respect to the normal auditory threshold.

Data on the correlation of the amplitude of the threshold excursions with the clinical condition is provided by Lundborg's (1952) results. Amplitudes of less than 3 dB. in the high frequency range occurred in all of 25 cases of acoustic trauma, and of less than 5 dB. in all of 26 cases of Ménière's disease. A mixed group of retro-cochlear (nerve or brain-stem) deafness showed amplitudes of more than 5 dB. One must therefore conclude that a small amplitude of the threshold excursions in the high

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frequency range is indicative, in psycho-physical terms, of complete asymptotic loudness recruitment and, in anatomical terms, of end-organ deafness.

This must not be constructed as implying that any type of loudness recruitment is indicative of an end-organ lesion. A number of reports have now accumulated showing the occurrence of loudness recruitment in cases of retro-cochlear deafness with the lesion located at practically any level in the auditory pathway, and de Bruïne-Altes (1946) early pointed out the difficulty of determining the connection between anatomical changes and the recruitment function. In an attempt to get the facts to fit the theory that loudness recruitment is due to end-organ deafness, a number of hypotheses have been advanced to explain the various discrepancies. First, the occurrence of loudness recruitment—complete in about 10 per cent. (Dix and Hallpike, 1958) incomplete in about 30 per cent. of cases (Dix *et al.*, 1948)—in acoustic neuromas is attributed by Dix and Hood (1953) to interference with the cochlear blood supply. This hypothesis receives partial confirmation by the disappearance of the recruitment phenomenon in three cases where the hearing was not abolished by surgical removal of the tumour (Dix and Hood, 1953; Simonton, 1956). Secondly, the occurrence of recruitment in perceptive bass deafness (which may be associated with a lesion almost anywhere in the auditory pathway) is exposed by Gravendeel (1958) as an artefact, since the patient will respond to the aural harmonics of the test tone. Thirdly, the occurrence of recruitment in brain stem lesions is attributed by Thiébaut *et al.* (1956) to a supposedly trophic influence or trans-synaptic degeneration of cochlear nerve fibres. Whilst the first two hypotheses are possibly acceptable, the third is less plausible. The greatest difficulty arises when we try to explain away the recruitment exhibited in a case of bilateral cerebral atrophy (Greiner *et al.*, 1959). However, it appears, from the data available (Dix *et al.*, 1948; Eby and Williams, 1951; Greiner *et al.*, 1956; and others) that, in cases where loudness recruitment occurs, complete recruitment is associated with cochlear deafnesses, and incomplete recruitment may be associated with retrocochlear deafness.

Reliability

We are unable to express this as a figure. The test-retest reliability for whether a continuously-recorded audiogram does, or does not, indicate recruitment is, however, very high.

Distribution of norm

Lundborg (1952) pointed out that, in the majority of cases, the amplitude of the threshold excursions varied between 6 dB. and 9 dB. The extreme limits of normality in his series were 5 dB. and 20 dB. Thus an amplitude of less than 5 dB. can be considered as indicative of recruitment.

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Advantages

The main advantage of using Békésy-type audiometry as an indication of the occurrence of loudness recruitment is that information on this point is obtained concurrently with a measurement of the auditory threshold. Moreover, since small excursions on the continuously-recorded audiogram are a correlate of complete asymptotic recruitment, which shows a high correlation with end-organ lesions, this test indicates not only the type of loudness recruitment but also more precisely the locus of the defect. Furthermore, this method does not rely on the presence of hearing in the other ear, as does Fowler's method.

Disadvantages

This method is not a valid test for the recruitment phenomenon occurring at frequencies of 2,000 c/s or less.

Indications

1. Where it is desired to obtain information on both the threshold of hearing and the recruitment phenomenon from one test only.
2. Where Fowler's alternate binaural loudness balance test cannot be applied i.e. (*a*) where the difference, at the relevant frequency, between the thresholds of the two ears is less than 20 dB. (*b*) where the difference, at the relevant frequency, between the two thresholds is greater than 45 dB. (Shadow hearing may then occur.) (*c*) where one ear is completely deaf.

It has been suggested that either Reger's (1936) monaural bifrequency loudness balancing test or measurement of the speech discrimination loss should be used as tests for the recruitment phenomenon if Fowler's test is not applicable. However, it is considered that bifrequency loudness matching is technically more difficult than Békésy-type audiometry. Moreover, Reger's test cannot be applied where the audiogram is horizontal. It can provide useful information on monaural loudness contours only when there is a localized or semi-localized depression of the auditory threshold curve. Although a poor speech intelligibility score at high intensity has been said to indicate recruitment, Pestalozza and Shore (1955) showed, on a large series of cases of presbyacusis, that a marked discrimination loss can exist in the absence of any loudness recruitment. Furthermore, a high discrimination score does not always predict the absence of recruitment (Hirsh *et al.*, 1954). Measurements of intensity or frequency difference limen have not yet been established as valid and reliable tests for loudness recruitment.

Contra-indications

Since the continuously-recorded audiogram does not provide valid information on recruitment at low frequencies, it should not be employed

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to detect this phenomenon in either cases of perceptive low tone deafness without appreciable involvement of the higher frequencies or of cases of perceptive bass deafness. Fowler's test is also not helpful in these two groups. Even in unilateral cases, the test frequently cannot be employed in the perceptive low tone deafness group since, if there is no appreciable involvement of the higher audio-frequencies, then there is unlikely to be an adequate impairment of the threshold to permit a loudness balancing test. In cases of the perceptive bass deafness group, the necessity of employing ipsilateral higher-frequency masking to prevent the perception of harmonics interferes with loudness judgments and vitiates the Fowler test. Cases of perceptive low tone deafness are eminently suitable for testing by measurement of the thresholds for aural harmonics. A low aural harmonic threshold is a good index of a cochlear lesion (Opheim and Flottorp, 1955).

III. Detection of Abnormal Auditory Adaptation (Per-Stimulatory Testing)

Schubert (1944) first showed that a drift may occur in the threshold of hearing of certain ears. If such a drift occurs in the continuously-recorded auditory threshold, abnormal per-stimulatory adaptation is said to be present. Subsequently, Dix *et al.* (1949) showed that the continuous stimulation of an ear with a tone of moderate intensity is associated with a decrease in the loudness of the stimulus when the intensity is measured by a simultaneous dichotic loudness balance. A decrease in the loudness of the continuous stimulus normally, but not invariably, occurs. If the decrease in loudness is marked, a state of abnormal per-stimulatory adaptation is said to occur. A Békésy-type audiometer is eminently suitable for detecting and measuring both these types of abnormal auditory adaptation.

Validity

The validity of both these types of measurements as tests for abnormal auditory adaptation is self-evident.

It has frequently been said that abnormal auditory adaptation at threshold is indicative of an ear showing loudness recruitment and, as a corollary, the absence of abnormal adaptation indicates a non-recruiting ear. This is incorrect. In contrast to Hood (1955) who infers that abnormal per-stimulatory adaptation at threshold is characteristic of recruiting type deafnesses, Kos (1955) claims that this phenomenon is characteristic of non-recruiting perceptive deafnesses. Palva (1958a) points out that the phenomenon can occur in either type of these perceptive deafnesses, but is infrequent in either group. It is the consensus of opinion that the phenomenon does not occur either with normal hearing or with conductive deafness. On two occasions however, the author observed threshold drifts

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in a normal ear. In both cases, the drift comprised an impairment of the threshold of about 20 dB., reaching a stationary level after 6-9 minutes and apparently following an exponential course. These records occurred in a series of more than a hundred threshold recordings on the same individual, which were taken during an investigation into post-stimulatory temporary hearing loss. It is therefore possible that this evidence of abnormal per-stimulatory adaptation is indicative of some damage, albeit temporary, to the cochlear nerve or end-organ. Kos (1955) has also reported that a case of pinealoma exhibited a marked threshold drift before there were any changes in the conventional pure tone audiogram.

Abnormal auditory adaptation at higher intensities has likewise been reported by Hallpike and Hood (1951) to be consistently present in recruiting type deafness. Palva (1955), however, found it to be present in only a fraction of recruiting perceptive deafnesses. Unlike abnormal adaptation at threshold, adaptation at higher intensities has not been noted in non-recruiting perceptive deafness.

Reliability

Inter alia, Egan (1955) studied the intra-observer variability of loudness matches in a person with normal hearing. His data indicate that the standard deviation increases from 5 dB. to 7 dB. during a sound stimulus lasting 3 minutes.

No statistical data are available on the reliability of abnormal per-stimulatory adaptation at threshold. Reger and Kos (1952), however, report that one person who showed a threshold drift was retested the following day with strikingly similar results.

Distribution of norm

Reger and Kos (1952) indicate that, at a given audio-frequency, the continuously-recorded normal threshold continues unchanged for at least one hour. Abnormal auditory adaptation at threshold shows as a threshold drift originating at the same time as the start of the test.

This "constancy" of the normal threshold is, however, with reference to the general trend. Fluctuations of the cursive threshold do occur. We have studied the continuously-recorded thresholds of four normally-hearing individuals at 4,000 c/s over a number of four minute periods. The first minute was allowed for the testing to be stabilized. The maximum fluctuation of the cursive threshold for each of the last three minute durations was measured. For a number of tests, the mean of these values was 2 dB. for three of the four observers.

Threshold drift should not be confused with what we would term threshold shift.* By this we mean sudden displacements of the cursive

* Davis *et al.* (1958) have recently advised the use of the term "threshold shift" to denote a change in the status of hearing, in the sense of temporary or permanent threshold shift. We would therefore qualify our use of the term by pre-fixing the word "sporadic".

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threshold of the order of 4 or 5 dB. This infrequently occurs in the tracings of normal ears.

Examination of Palva's (1955) data on per-stimulatory adaptation at supra-threshold levels indicates that the adaptation loss for normal ears and non-recruiting deafnesses (including conductive losses) is 20 dB. or less. On an average it was less than 10 dB. This applied to tones of 500, 1,000, 2,000 and 4,000 c/s and at 60 or 80 dB. sensation level with measurement at the end of continuous stimulation for a period of three minutes.

Advantages

These tests for abnormal auditory adaptations are, in practice, straight-forward and reasonably simple.

Disadvantages

The significance of results from auditory adaptation tests is, as yet, uncertain so that the place of such tests in clinical otology remains to be established.

Indications

Palva (1958a) says that the presence of a large adaptation loss at louder levels may illustrate the difficulty that some perceptively deaf ears have of listening to a loud speech or using a hearing aid. The test may therefore be used in cases of recruiting perceptive deafness where we require information on this point. However, less than 16 per cent. of this group of cases show an adaptation loss of 25 dB. or more at supra-threshold levels (Palva, 1955).

Contra-indications

Since conductive deafnesses do not manifest abnormal auditory adaptation, there is no point in employing either test in these cases.

IV. Measurement of Abnormal Fatiguability and Re-adaptation (Post-stimulatory Testing)

In this section, various factors connected with temporary hearing loss following noise exposure are considered. The terminology used by different workers is somewhat varied and, to a certain extent, confusing. These effects, involving noise-induced temporary hearing loss are variously designated "fatigue", "re-adaptation" (in the sense of recovery of the normal threshold), "temporary threshold shift", "recovery". These various terms may have specific connotations in the minds of the authors so that when particular work is quoted the terminology is retained.

Post-stimulatory tests have been employed in auditory examination for a much longer period than the per-stimulatory tests and their results

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have been used both in attempting to predict the type of lesion and in evaluating the individual's susceptibility to noise trauma (Palva, 1958a). As long ago as 1929, Temkin suggested that the susceptibility of potential workers in noisy industries should be assessed by an auditory fatigue test. Huizing (1948) claimed that recruiting type deafnesses consistently showed appreciably more post-stimulatory auditory fatigue than other cases. In view of the suitability of Békésy audiometry for recording the recovery from temporary hearing loss, as in such susceptibility tests, the validity of the latter must be examined.

Validity

Wilson (1944) tested 108 newly-enlisted soldiers by fatiguing their ears with a 2,048 c/s tone at 80 dB. for 8 minutes and noted those who showed a hearing loss of greater than 10 dB., 1 minute afterwards. After two or three days on the rifle range, audiograms were obtained from each soldier. Those who showed a hearing loss of 10 dB. or more at one or more of the audiometric frequencies were considered "susceptible". Wilson's results indicate a high degree of correlation (coefficient of association of 0·91) between his predictive test and the subsequent audiometric changes.

Jerger and Carhart (1956) measured the time required for the auditory threshold at 4,500 c/s to return to within 20 dB. or 10 dB. of the testing value after fatiguing with a 3,000 c/s tone at 100 dB. for 1 minute. A group of jet engine mechanic trainees was tested in this manner before being subjected to occupational noise. Eight weeks after a 3 day period of noise exposure, the mean hearing losses at 3,000 c/s and 4,000 c/s were measured. A small but significant positive coefficient of curvilinear correlation was obtained between the post-stimulatory temporary threshold shift and the high tone hearing loss.

Neither Wilson nor Jerger and Carhart used Békésy audiometry, but continuous tracking of the post-stimulatory threshold with such an instrument is well suited to the precise determination of the auditory threshold at a specified time and can be used with advantage in such procedures. Consequently, this validation of post-stimulatory threshold measurements as a predictive test for either occupational noise or acoustic trauma will also apply when a Békésy audiometer is used for these tests.

With reference to abnormal post-stimulatory fatigue as a valid test for recruiting type deafness, Palva (1958b) showed that conductive deafnesses and non-recruiting perceptive deafnesses gave essentially the same results as normal ears. Only 28 per cent. of his recruiting type deafnesses showed a post-stimulatory threshold shift that was significantly greater than the normal response. This applied to a point 1 to 2 minutes after the termination of a stimulatory tone of 2,000 c/s, 3,000 c/s or 4,000 c/s at 30 dB. sensation level for 3 minutes, with measurement of the threshold at the same frequency.

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Reliability

Inter alia, Lightfoot (1955) investigated the test-retest reliability of auditory threshold shifts at 3,000 c/s and 4,000 c/s following stimulation for 3 minutes at 105 dB. S.P.L. with white noise or a 2,000 c/s tone. In general, the reliability was highest for the noise/4,000 c/s combination, where a correlation coefficient of 0·77 obtained 2 minutes after stimulation, and of 0·81, 6 minutes after stimulation. Surprisingly, the correlation coefficients for the tone/3,000 c/s combination did not reach significance value. The largest inter-subject as well as the smallest intra-subject

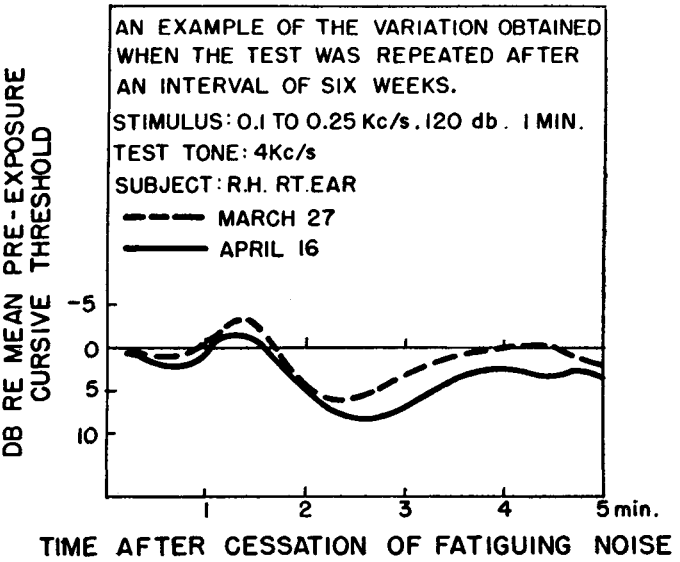


FIG. 2.

An illustration of the repeatability of changes in the threshold of hearing following stimulation with a high sound pressure level auditory stimulus. (After Hinchcliffe, 1957.)

variability was associated with the noise/4,000 c/s combination. Moreover, this combination also has considerable face validity as a predictive test for susceptibility to acoustic damage since occupational noise hazards are rarely in the nature of a pure tone and the locus of initial hearing loss is usually around the 4,000 c/s region. Perhaps if Jerger and Carhart had used this combination they might have obtained a higher correlation coefficient in the validation of their test.

Palva's (1958b) data shows a standard deviation of the mean post-stimulatory threshold of about 2 dB. This result was obtained on one normally hearing individual. It is of the same order as the standard deviation of the resting threshold of the normal ear.

A graphic example of the test-retest reliability of the pattern of post-stimulatory threshold changes is shown in Fig. 2.

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In this case, the stimulus was a narrow band of noise with a lower cut-off frequency of 100 c/s and an upper cut-off frequency of 250 c/s. The stimulus intensity was 120 dB. S.P.L. and the duration 1 minute. The cursive thresholds are shown for two recordings separated by an interval of 6 weeks. The diagram also demonstrates that, under appropriate conditions of stimulation, a polyphasic, or oscillatory, form of recovery curve occurs.

Distribution of norm

Palva (1958b) considers that, for diagnostic purposes, a threshold shift of more than 14 dB. at 2,000 c/s (occurring 90 or 120 seconds after 3 minutes' stimulation with a tone of the same frequency at 30 dB. S.L. for 3 minutes) is abnormal; this, he believes, indicates a recruiting type of ear which is also abnormally susceptible to auditory fatigue.

Advantages

Since the curve of re-adaptation/recovery after auditory stimulation/fatigue is not simply a monotonic process (Bronstein, 1936; Hirsh and Ward, 1952 and others), continuous tracking of the auditory threshold is not merely an advantage, it is a necessity.

Disadvantages

With regard to the diagnostic value of post-stimulatory threshold studies, abnormal tracings occur in an insufficient number of recruiting-type deafnesses for the test to be used to detect this condition.

In the case of predicting an individual's susceptibility to permanent noise-induced hearing loss, this type of test is still somewhat in the experimental stage, despite a limited validation and the establishment of high reliabilities for certain stimulus/test tone combinations.

Indications

As a predictive test for noise susceptibility.

Contra-indications

There are no serious contra-indications, except that caution must be used in applying high sound pressure levels to individuals with recruiting-type hearing defects.

Operating Characteristics

Although operating characteristics have been laid down for the conventional pure tone audiometers (British Standard 2980: 1958), there are, as yet, no standards for Békésy-type audiometers. Clearly, however, many of the criteria in B.S. 2980 can be applied to the Békésy-type audiometer,

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but there are additional variables such as attenuation rate of the test tone, duration of frequency sweep, recording paper speed and the features of the pulsed tone, if this is used.

Békésy's (1947) original instrument had an attenuation rate of 140 dB./minute and this has been adhered to both by Lundborg (1952) and by Palva (1958b), who have both had the instrument in clinical use. Other workers have used lower attenuation rates for continuous tracking of the threshold. Thus Burns and Hinchcliffe (1957) and Lierle and Reger (1954) have used 120 dB./minute and Jerger (1956) has used 60 dB./minute. In a comparison of three attenuation rates, 30 dB./minute, 60 dB./minute, and 120 dB./minute, Corso (1955) considered that 30 dB./minute was the optimum rate. However, Epstein and Schubert (1957) increased their rate of intensity change from the conventional 120 dB./minute to 258 dB./minute since this tended to keep their listeners more alert as the tone "appeared" and "disappeared" relatively rapidly. All these rates apply to continuous test tones. For a pulsed test tone, the author has found that 180 dB./minute gives reliable results.

Paper speeds of 8·3 mm./minute and 33 mm./minute have been used by Lierle and Reger (1954), 38 mm./minute by Lightfoot (1955), 19 mm./minute by Hinchcliffe (1957), 10 mm./minute by Burns and Hinchcliffe (1957) and 12 mm./minute by Palva (1958b). A suitable relationship between the dimensions of the vertical (decibel) scale and the horizontal (paper traverse) scale should be maintained to make the individual excursions well defined and the frequency scale sufficiently open for accurate reading. In practice, paper speeds of about 10 mm./minute are compatible with an easily read scale on both axes.

In Békésy-type audiometers, the frequency change is at a constant rate when the frequency is expressed on a logarithmic scale. Békésy's original audiometer covered the range 100 c/s to 10,000 c/s in 15 minutes and this rate has been largely adhered to by subsequent users of this type of audiometry. In one study, the author used an audiometer that covered the range 500 c/s to 6,000 c/s in nearly 8 minutes. This approximates to the rate used by Békésy. Obviously, if the frequency sweep takes a long time, measurement of the threshold by this method becomes time-consuming. Conversely, if the sweep is too quick then the small high tone notches, which this method is suitable for detecting, will be missed. Corso (1955) investigated the test-retest reliability for Békésy audiometry when the sweep from 250 c/s to 8,000 c/s was performed in 5 minutes, 10 minutes and 20 minutes. The reliability was highest for a time of 10 minutes. Coverage of the audio-frequency range in 9 minutes, with a paper speed of 9 mm./minute, would produce a record of convenient size.

To counteract possible disturbing effects of tinnitus, Harris (1954) incorporated an electronic interrupter in his apparatus to give a pulsed test tone. This is a useful modification to the original Békésy audiometer,

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especially when post-stimulatory studies are contemplated. Moreover, a pulsed tone is easier to listen to, and a decision of "heard" or "not heard" can be the more easily arrived at. It has been found that a repetition rate of 100 interruptions per minute (i.p.m.) with a duty-cycle of 0·5 and a rise and fall time of 50 milliseconds is suitable. This gives a pulse of 300 milliseconds duration. As mentioned previously, Palva (1956a) found that a pulsed tone of 120 i.p.m. with a duty cycle of 0·5 gave essentially the same threshold measurements as a continuous tone over the frequency range usually covered by clinical audiometry. Appreciably slower or greater rates of interruption resulted in absolute thresholds different from those given by a continuous test tone. Excessive frequencies of modulation introduce other frequencies of increasing amplitude into the test tone so that we are no longer dealing with a pure tone (Garner, 1947). The purity of the test tone must be safeguarded by limitation of the onset and decay rates and by adequacy of duration of the pulses.

Control

As much rigid control, in the form of calibration and monitoring, is necessary for self-recording audiometry as it is for conventional pure tone audiometry. We have recently surveyed the technique of threshold air-conduction audiometry (Hinchcliffe and Littler, 1958) and much of this is applicable to Békésy-type audiometry. In addition, control over the mechanical mechanism is necessary in self-recording audiometry. Care should be taken that the frequencies and intensity levels indicated on the recording paper agree with the outputs of the audiometer at these points. Attention should be paid to the mechanism which is incorporated in some audiometers to convert the curvilinear absolute threshold of hearing, combined with the effect of variation of the sensitivity of the telephone with frequency, to the horizontal line of the audiogram's normal hearing reference zero. Defects of this may show a false hearing loss for the higher frequencies and intermittent faults may indicate a false per-stimulatory threshold drift.

Conclusions

Békésy-type audiometry provides a valid, reliable measurement of the auditory threshold and a valid, reliable index of the presence of complete asymptotic loudness recruitment when this is producing a hearing defect involving the higher frequencies. The Békésy audiometer also provides a suitable instrument for investigating hearing changes during and after acoustic stimulation.

Not only is the continuously-recorded audiogram no less reliable than the conventional octave audiogram but its superior resolving powers in terms of frequency make it a more sensitive index of small changes.

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Self-Testing Automatic-Recording Audiometry

If a universally acceptable test for predicting sensitivity to noise-induced hearing loss is developed, it would appear probable that the Békésy-type audiometer will be employed to perform this test. For this reason, and its ability to detect incipient traumatic notches on the audiogram, the Békésy audiometer should also find employment in the hearing conservation programmes which are now being introduced in connection with noise hazardous occupations.

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