HEARING TESTS.*

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FEW specialties can have less reason than the otological to be satisfied with their functional tests, and I propose therefore to review the present methods, to emphasise their shortcomings and to describe means of placing auditory tests on a rational, accurate and convenient basis.

Qualitative Tests in Present Use.

Tests concerned with Limitation of Tonal Range.—While curtailment of tonal range is a quantitative rather than a qualitative defect, it is best considered with the latter tests. There is never justification for a declaration, based on a functional test, that a patient has no hearing for any particular note, for there is always the possibility that with greater intensity of sound some perception would have been manifested. The term "limit of tonal range" is, however, useful in practice, but the instrument employed in its determination should be mentioned, as affording evidence of the intensity of vibration.

The lower limit is usually tested with tuning-forks, and with these 16 d.vs. per second is the figure most generally accepted for the normal lower limit. The testing of patients with low forks requires care; the vibrating prongs must not touch the hair or auricle, and overtones must be guarded against. Suitable construction of the fork, with adequate clamping, and striking the fork in the middle of its length against a soft object (*e.g.*, the hypothenar eminence of the hand) minimise the production of overtones. If anomalous results are obtained, the patient should be asked to describe what he hears; only a small amount of intelligence is required to differentiate the low-pitched fundamental from the overtones.

The upper limit of audition has been very variously estimated, frequencies of from 15,000 to 41,000 d.vs. per second having been suggested. As with the lower limit, a precise figure is of small value unless the approximate intensity of vibration, evidenced by the instrument employed, is known.

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For testing the upper limit audiometers, Koenig's cylinders, Galton whistles and the monochord may be employed.

For general purposes in testing tonal range limits, audiometers are not of great value. That described by Tucker[1] in 1922 conveniently exceeds the "normal" upper limit, while a further example with a high upper limit has recently been demonstrated by Popper.[2] Koenig cylinders[3] provide notes of constant pitch but with variable intensity. They are inconvenient and not of general utility. Galton whistles were introduced by Burkhardt-Merrian in 1878.[4] Modifications have since been made, notably by Edelmann and Schafer. Using this last modification I have found the normal upper limit to be about 19,000 d.vs. per second. The frequency is determined from the scale reading and a table supplied by the manufacturers. The formula which is the basis for such determination is $n = \frac{v}{4L}$, where n is the frequency, v the velocity of sound (in air 331 metres per second), and L is the length of the tube. Temperature affects the result. Thus at 0° C. a tube length of 5 mm. corresponds to a frequency of 16,550 d.vs., but at 25° C. to one of 17,300. This is in accordance with the formula $V_t = V_0(1 + \cdot 00183\, t)$.

The monochord is, I believe, the most convenient and accurate agent for testing the upper limit. While it may be made, by plucking the wire, to yield transverse vibrations, these are of a relatively low frequency which varies not only with the length but also with the mass and tension of the wire. The value of the monochord lies in the fact that, when rubbed with a spirit-moistened applicator, the wire is set into longitudinal vibration, and the pitch of the resultant sound depends only upon the length of the vibrating wire. The frequency is determined by the formula $v = 2Ln$ (where v is the velocity of sound in the wire; in the steel monochordal wire this is about 499,000 cm. per second; L is the length of the vibrating wire, and n is the frequency, in double vibrations per second). The length of the vibrating wire is given by the centimetric reading on the monochord. One may say then that

$$n = \frac{499{,}000}{2 \times \text{centimetric reading}}$$

Though the frequency is independent of the mass and tension of the wire, these are not without influence on the result, since

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they affect the intensity of the resulting sound. Decreased intensity may, of course, spuriously suggest a lowering of the auditory upper limit. It would be convenient to have the frequencies engraved on the monochord in place of the usual centimetres.

Few patients have difficulty in determining the upper limit by the monochord, the change from a squeak to a rub being easily recognised. I have found the normal limit by the monochord in young adults to be about 20,500 d.vs. per second, variations occurring even in the individual. The limit when tested with the whistle is rather lower than this, a finding which might be due to the whistle giving less intensity of sound at these high pitches, or perhaps to the masking effect of its associated blowing sound.

The monochord has the advantage that its sound may be transmitted by bone conduction. In so using it I found one thing for which I was not prepared, that in every case, even of perceptive deafness, the upper limit is lower by air than by bone conduction. In cases of obstructive deafness such a finding is not unexpected, but its occurrence, often to a marked degree, in cases of perceptive deafness is remarkable. A paper just published by Sonnenschein[5] records the same finding in health; he quotes Kalaehne for an explanation. It is there suggested that in using tuning-forks one is comparing the incomparable; that in testing air conduction one is utilising the transverse vibrations of the prongs, which are "proper" to the fork, and that one compares this with bone conduction excited by the incidental and weak longitudinal vibrations in the stem of the fork. With the monochord equal longitudinal vibrations supply the stimulus for both air and bone conduction. This is, I think, the probable explanation.

Tests dependent upon Perception by Air and Bone Conduction and their Relative Proportions.—These tests form the backbone of our functional diagnosis, and I believe that the lack of otological progress in the last thirty years is largely due to their inherent inaccuracy.

Under this heading fall Rinne's test, Schwabach's test, Weber's test and Bing's test, all being closely related. *Rinne's test.*—If duration of perception of the sound of a tuning-fork placed on the mastoid is greater than when the prongs are held close to the tragus, Rinne is said to be negative; if this is reversed, as normally, Rinne is said to be positive.

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Schwabach's test.—The base of a tuning-fork is placed on the patient's mastoid; when perception ceases it is transferred to the observer's mastoid. If the observer hears the fork, Schwabach is minus, and may be expressed as so many seconds deficiency. If, on the other hand, by reversing the order of the test, it is found that the patient's perception by bone conduction exceeds that of the normal person, Schwabach is plus so many seconds. *Weber's test.*—The base of a tuning-fork is placed on the middle line of the skull; if perception is stronger (or longer) in one ear than the other, Weber is said to be lateralised. *Bing's test.*—The base of a tuning-fork is placed on the mastoid; when hearing ceases the meatus is occluded; if the fork is again heard Bing is said to be positive.

Rinne suggested, as a rule for tuning-forks, that normally perception by air conduction is twice as long as by bone conduction. Such a statement, of course, does not stand the shortest scrutiny. In 1855 he described his test,[6] which depended upon inversion of this air-conduction bone-conduction ratio and which differentiated conductive from perceptive deafness. It was soon recognised that the test was not free from fallacy, and Bezold[7] suggested that its value was limited to cases with more than a certain defined grade of deafness. This only implied recognition of the fact that the point of change from a positive to a negative Rinne is only an arbitrary point on a sliding scale. Attempts have been made to assess the full number of possible results of the test, as many as eight having been suggested by some authors.[8, 9]

The pitch of the tuning-fork plays a great part in determining the result of the test, the lower the pitch the less severe the lesion required for a negative result. This is due to the fact that, in conditions giving rise to a negative Rinne, perception by air conduction for the lower notes is more affected than that for the higher notes.

Schwabach's test is based upon one of the factors of Rinne's test—the lengthening of perception by bone conduction in conductive deafness. It was promulgated by Schwabach in 1891.[10]

Weber's test rests upon an observation made by Weber in 1834.[11] He noted that obstruction of the auditory meatus caused lateralisation of perception of a tuning-fork, placed mesially on the skull, to the ear in question. This observation was then extended to cases of conductive disease, and the test established for cases of unilateral, or unequal bilateral

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disease. Attempts have been made by G. W. McKenzie[12] to assess the results of the test quantitatively by recording the distance from the middle line to which the fork can be moved without changing the lateralisation of perception. While possibly attractive theoretically, such a suggestion can only be based upon lack of practical knowledge. In a normal person a tuning-fork, placed upon one frontal or parietal eminence, is heard more strongly in the opposite ear; observations on such apparently anomalous perceptions of tuning-forks placed in various positions on the skull have appeared in a paper by Frey.[13] These facts stultify any such mode of estimation of the test.

Bing's test[14] is closely associated with the preceding ones; it is only an expression of Weber's observation, since it relies upon the increased perception by bone conduction which occurs on closing the meatus in all cases in which such increase is not already present and maximal as a result of conduction disease.

The Schwabach, Weber and Bing tests agree with the Rinne test, in that, in cases of conductive disease, the lower the fork used the more readily is an appropriate response elicited. These four tests fail to justify their prominent place in the routine testing of patients, because they are an unnecessarily complicated method of obtaining incomplete and frequently misleading information. The Rinne test may give positive or negative results. Surely we are entitled to expect that the results of so elementary a test should establish unequivocal conclusions? Yet we have to consider full positive results, reduced positive results, positive-negative results, reduced negative results and full negative results, at the end of which we can really be said to have a very incomplete knowledge of the auditory pathology. The Schwabach test may sometimes provide information, though it is always incomplete and sometimes misleading; it cannot serve as anything more than a conjecture as to the aural condition. Bing's test may provide information as to the presence or absence of gross conductive disease; its value ends there. Weber's test is an attempt at a short cut, inasmuch as it would provide information by the comparison of two unknowns (the two ears); as such, it fails lamentably. While in unilateral disease of pure conductive type it may yield information, in all other cases the results are indefinite or unreliable.

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Complementary Tests.—Before leaving the subject of tests in present use, one other test requires consideration, being attractive in theory and disappointing in results—Gellé's test.

Gellé's test was put forward in 1881,[15] and has since met with much theoretical and practical criticism. Gellé supposed that the increased pressure in the external auditory meatus produced in performing the test caused inward movement of the drumhead and ossicular chain, with consequent raising of labyrinthine pressure by incursion of the stapedial footplate; the rise of labyrinthine pressure resulted in diminished sensibility of the cochlear organ, manifested by decreased perception of a tuning-fork by bone conduction. Stapedial fixation would prevent such a sequence and there would be an absence of the normal response.

In an attempt to assess the value of the test, I have carried it out in a number of cases. While deserving fuller consideration, the following figures, from the last eighty cases examined, may be interesting as affording information as to its occurrence and ground for criticism of the theory of its production.

TABLE I.—*Gellé Test.*

160 ears examined :—

(A) 20 per cent. otosclerosis of the Bezold triad type.

(B) 29 per cent. with perforated drums.

(C) 51 per cent. with whole drums (this group includes normal ears, C.C.O.M., C.S.O.M. residua, and cases with perceptive deafness, but excludes the otosclerotic group).

	Gellé Result.		
	Positive.	Negative.	Reversed.*
All ears examined . .	79·0 per cent.	15·0 per cent.	6·0 per cent.
(A) Otosclerosis . . .	66·0 ,,	15·5 ,,	18·5 ,,
(B) Perforated drums . .	78·5 ,,	21·5 ,,	0·0 ,,
(C) Whole drums . . .	83·0 ,,	11·0 ,,	6·0 ,,

* By reversed Gellé I mean increased loudness of the sound occurring during increase of meatal pressure.

The grouping of cases and the results, expressed in Table I., in addition to calling attention to the existence of a reversed Gellé, lead to the following suggestions. Firstly, that otosclerosis has little or no influence on the result. Secondly, that the test is unsound in theory, for the test is as frequently positive when the drum is perforated as when the drum is whole; if the drum is perforated there can be no mass inward

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movement of the ossicles, and it is probable that the increased pressure is transmitted to the labyrinth at least partly by the round window; indeed one would expect more by the round window than the oval window, for one knows that the membrane of the former is normally considerably more lax than that of the latter. Thirdly, one would suggest that the significance of the Gellé phenomenon is still unknown.

Gellé's test consists essentially, as stated, in the variation of perception of a bone-transmitted sound, and one might criticise the attachment of Gellé's name to a test described in a recently issued pamphlet. In this test a nozzle attached by rubber tubing to a valveless Politzer bag is inserted into the meatus. A sounding tuning-fork is placed on the bag, and pushed in to cause compression, variations in the subject's perception being noted. In this test the sound is transmitted by air conduction, and a factor entirely different from any in the true Gellé test is introduced, that is, variation in the tension of the ossicular chain while conveying the sound-waves. This new test may possess considerable value, but to call it Gellé's test can only lead to confusion.

Suggested Improvement in Qualitative Testing.

Since auditory ability may be considered as being the total hearing which is the result of the co-operation of conductive and perceptive components, it is obvious that by determining the condition of any two of these we can deduce the condition of the third. The Rinne and associated tests fail in their purpose of locating an auditory defect because their results are influenced simultaneously by changes in both components of the auditory function, conductive and perceptive. The total hearing or auditory ability (that is to say the hearing as normally considered by air conduction) is of course readily determined; its precise estimation will be considered in the third section of this paper (p. 93). The primary determination of conductive function is obviously difficult, either by subjective or objective methods, though Bing's test may sometimes provide an approximate indication.

The perceptive component is readily determined and may be accurately assessed by a test which has been long described but which has never secured the universal appreciation it deserves. That is by the comparison of the subject's absolute bone conduction (*i.e.* perception of a tuning-fork placed on the

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mastoid, the meatus being closed by the finger) with a normal person's absolute bone conduction.

This test was described as long ago as 1883 by Pomeroy,[19] and Hallpike[20] describing some cases recently stressed its value; Mr Somerville Hastings has long used it as a routine.

If we were to accept the various theories involving the participation of the tympanum, drumhead and ossicular chain (Bezold[21], Gray[22], Kerrison[23]), in auditory perception by bone conduction, we might doubt the test as an index of purely perceptive function. But the test supplies the chief contradiction to the theories, for almost complete destruction of the drum, disruption of the ossicular chain or the occupation of the tympanum by fluid or organised contents cause no appreciable difference to perception by bone conduction so tested.

The performance of the test requires little notice, but there are one or two elementary points requiring attention. The meatus is best closed by pressure of the tragus inwards by the examiner's finger; certain wiry and inefficient tragi do not yield to such treatment, and in these cases the patient's moistened finger should be inserted into the meatus. Occlusion is aimed at, an increase of pressure is to be avoided, for gross increases of pressure may cause diminution of perception by bone conduction (Gellé's test—the result being undoubted, even if the suggested mechanism is uncertain). The pressure of application of the tuning-fork should be the same when testing the patient as when comparing with the normal; this is considered in greater detail later, on page 100 of this paper; little practice is necessary to attain this equality. Any fork between 128 and 1024 d.vs. per second may be employed. The 256, 512 and 1024 forks are most suitable and give readily defined end-points; the sound of the 128 fork is sometimes confused with a low-pitched noise which may be heard in the ear during occlusion of the meatus.

In the normal person perception by absolute bone conduction (T.F. stem) is slightly less than by air conduction (T.F. prongs) (*vide* p. 101 for this constant normal relationship).

Conductive disease results in loss of hearing power by air conduction (A.C.) with normal perception by absolute bone conduction (A.B.C.); if more than of the very slightest degree, much less than that required to give a negative Rinne, it will result in reversal of the A.C.-A.B.C. relation. Perceptive deafness involves diminished hearing by both A.C. and A.B.C.,

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the excess of A.C. over A.B.C. being if anything increased. A mixed deafness will cause loss by A.B.C. with greater and disproportionate loss by A.C.

It might be apposite here to compare the tests of absolute bone conduction and relative bone conduction (Schwabach). The most important differences lie in the fact that absolute bone conduction affords an absolute index of the perceptive function, whereas relative bone conduction is influenced perhaps simultaneously by changes in both perceptive and conductive functions and is therefore indicative of neither. There is a further difference which becomes evident during the test, in that the absolute bone conduction test requires the use of a Bárány noise machine, in the opposite ear to that tested, less frequently than the relative bone conduction test. Consideration of this question requires some examination of the mechanism of transmission of sound by bone conduction.

It is almost correct to say that bone conduction as such does not exist, *i.e.*, that when a sounding tuning-fork is placed on the skull, the sound vibrations are conveyed to the cochlea not by conduction as such but by sympathetic resonance of the cranial structure. This being the case, one would expect that the effective stimulus as the result of the application of a fork to the skull would be no greater in the region of application of the fork than at a distance, and it is indeed upon this fact that the theory is postulated. In this paper I use the term "bone conduction" without qualification, meaning not conduction as such but conduction by resonance. The existence of this conduction by resonance conveys important implications, affecting the performance of and deductions from the tests; the evidence for it is therefore important.

In a normal person place a sounding tuning-fork on, say, the right mastoid, and occlude the left meatus. The fork is heard in the left ear. Immediately perception ceases, close the right meatus; the fork is heard either not at all or for a time so short that it might be explained by fatigue of the left ear. Again, take a person with a unilateral nerve deafness; absolute bone conduction in the better ear is equal whether tested from the same or the opposite mastoid. Therefore, so far as absolute bone conduction is concerned, the stimulus is equal throughout the skull, and is not greater in the region of application of the fork; that is, there is not true conduction but conduction by resonance.

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In regard to relative bone conduction one cannot be quite so definite, as it is possible that there is slight weakening of the stimulus at a distance from the point of application of the fork, but if this is so it is very much less than is commonly accepted. If one takes the effective stimulus to the cochlea of the same side to which the tuning-fork is applied as 25, the effective stimulus to the opposite cochlea is certainly not less than 23. This is again readily and similarly demonstrated.

This cross stimulation dependent upon bone conduction by resonance is not sufficiently recognised, and as a result many tests are invalidated. Its importance appears in the accompanying Table II., in which are set forth the occasions on which the use of a Bárány box is necessary. Quantitative work has shown that for a fork of 512 d.vs. frequency, in a normal person, if the sensitivity by air conduction is 100, absolute bone conduction has a value of 50 and relative bone conduction a value of 25. These figures are utilised in the Table; their precise estimation and significance will be discussed later.

TABLE II.

Condition of Opposite Ear.	Ear Tested.	
	Relative Bone-conduction Test (Schwabach).	Absolute Bone-conduction Test
Normal 23	50 ↑ **25** ↓ 23 Bárány necessary for all grades of N.D.	**50** ↓ 23 Bárány necessary for more severe grades of N.D.
Nerve deafness	50 ↑ **25** ↓	**50** ↓
Less than 23	Less than 23 Bárány necessary for grades of N.D. approximating to or exceeding that in opposite ear	Less than 23 Bárány necessary for highest grades of N.D.; exceeding by a fair margin that in opposite ear
Conduction deafness 50	50 Bárány necessary for all grades of N.D.	**50** Bárány necessary for all grades of N.D.

N.D. = Nerve or perceptive deafness.

The figures express sensitivity, the stimulus to the opposite ear being regarded as coming from a fork placed on the mastoid of the ear being tested.

The figures in heavy type in the last two columns represent the normal findings; the arrows show the possible range of results of the respective tests.

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Hearing Tests

Obviously it is impossible, without special precautions, to demonstrate any loss of sensitivity greater than that which requires a stimulus so loud as to affect the ear opposite to that tested. If this crossed sensation is anticipated one must exclude the other ear by the use of a Bárány noise machine. Now, in the Schwabach bone conduction test, the normal sensitivity of the two ears is equal, and therefore to demonstrate any degree of reduced sensitivity a Bárány box is essential. But in the absolute bone conduction test the normal sensitivity (50) of the ear tested is raised considerably above that of the opposite ear, where, the meatus not being closed, ordinary or relative bone conduction rules (25). It is thus possible to demonstrate a considerable degree of nerve deafness before a Bárány box becomes necessary.

Quantitative Estimation of Total Hearing.

Unsatisfactory though qualitative aural tests are, quantitative testing, where it exists at all, is still more unsatisfactory. Though otology is never likely to become an exact science, there is great need for a method of quantitative testing on an agreed basis which will yield accurate results which will be comparable wherever obtained.

Various modes of expression of hearing defect have been suggested; in arbitrary units, in physiological units — the sensation units of the American School (24) — in intensity units, and on a hearing distance basis. Of these, the last is of most value, affording results which are intelligible even to the untrained mind, and which have a sound physical basis.

By this method we express hearing power as a fraction, *i.e.*:—

$$\frac{\text{The distance at which the subject hears a sound}}{\text{The distance at which a normal person hears the sound}}$$

or, better, we express this as a percentage. This we call the percentage retention of Normal Hearing Distance (percentage N.H.D.).

By this method we are at once presented with a defined mental picture of the degree of deafness; for example, it is obvious at once that a person with 10 per cent. N.H.D. can hear a sound at only one-tenth of the distance at which a normal person hears that sound. Moreover, it is a natural instinct to speak of deafness, the loudness of sounds and hearing generally in terms of distance. As a result the tests that have been most used, the ability to hear the voice, the watch, and Politzer's acoumeter, are on a distance basis.

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Brief consideration may be afforded the means of sound production employed in quantitative testing. The human *voice* has long been used for such tests, and inasmuch as the ability to hear and understand speech is the criterion *par excellence* of hearing ability, it is unfortunate that its disadvantages outweigh its advantages. Three degrees of intensity are generally recognised—the shout, the conversational voice, and the "residual" whisper. The Normal Hearing Distance for each varies with the lung-power and mood of the observer, and the needs of the occasion. In using the test, note must be made of the test words employed, for the various consonants and vowels (according to their pitch) differ greatly in their carrying power, and are variously heard in the different types of deafness. The difficulties in the production of a standard voice are insuperable; attempts have been made by the use of phonographs and electrical apparatus to overcome these difficulties, but the success is not sufficient to lead one to expect their general application.

The ability to hear *a watch* is a most convenient test of hearing, and the results are on the rational hearing distance basis. The normal hearing distance for the watch under quiet conditions is usually underestimated, but in the expression of results the Normal Hearing Distance should be that for the conditions at the time of testing, though this may lead to some overestimation of the patient's hearing power, since a deaf person is less affected by extraneous noise than a normal person. An *Acoumeter* was devised in 1877 by Politzer,[25] who hoped for the production of an instrument which would give a standard intensity of sound. The difficulties of production have apparently been too great, for acoumeters are encountered which vary widely in loudness. The normal hearing distance is some 40 feet; the distance being so great, it is impossible to determine the N.H.D. under the conditions of each test. To express the patient's hearing power as

$$\frac{\text{Patient's H.D. for the acoumeter}}{\text{40 feet}}$$

must usually lead to an exaggeration of the patient's hearing defect. As in the case of the watch, a high-pitched noise is produced, the tones averaging some 2800 d.vs. per second. Care is necessary in testing, for with these high-pitched sounds, reflections from walls and other objects are particularly liable to vitiate the result.

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Hearing Tests

Various electrical audiometers have been described. Probably the first was that of Urbantschitsch,[26] who in 1890 described an audiometer which had frequency variable by a Neef's hammer, intensity variable by the separation of two coils, and a telephone for the production of sound for the patient. Some years later (1893), Gradenigo[27] had an audiometer, which was, however, limited to one frequency. In 1897, Seashore[28] produced an audiometer which has since been subject to considerable improvement; it is now known as the Iowa pitch range audiometer.[29, 30] Later audiometers have taken advantage of the wireless valve; examples are furnished by the Tucker audiometer,[1] the Lowndes Yates audiometer, and the models of the Western Electric Company of America. The Iowa pitch range audiometer and the Tucker audiometer at present give results merely in arbitrary units, *i.e.*, of electrical current. The Western Electric Company audiometers have been so adjusted as to read in terms of physiological units, the so-called sensation units. Although possessing advantages in the rapidity with which complete quantitative tests may be carried out, in the continuity of their tonal range and in the reduction of the personal factor to a minimum, I believe that, on account of their complications, lack of portability, and cost, they will never come into routine use.

Tuning-Forks. — Tuning-forks forming a part of the equipment of every otologist, essential for the performance of qualitative tests, it is natural that attempts have been made to utilise them in quantitative testing. Since they can provide accurate information as to quantitative defect in hearing, and since their results can be expressed in terms both convenient and universally applicable, such use deserves considerable attention.

The value of tuning-forks in quantitative testing was first suggested by Conta in 1864.[31] He observed the duration of time the patient heard the fork, counting from the moment of striking the fork, and expressed the result as a fraction—this period over the normal period of perception of the fork. His results must have been completely lacking in accuracy and value. Some years later Magnus[32] also suggested their value, and expressed his results in a similar way. The expression of hearing defect in terms of duration of perception of tuning-forks then became very widespread, and two schools became apparent; the one was content to express hearing defect as the number of seconds deficiency for a fork, *i.e.*, the number of

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seconds a fork is audible to a normal ear after it had ceased to be audible to the deaf ear, the distance being the same; the other school expressed the result as a fraction:—

$$\frac{\text{Duration (number of seconds) of perception of fork by patient}}{\text{Duration of perception of fork by normal person}}$$

(Hartmann, etc., *vide* Dundas-Grant [33]).

The expression of hearing power merely as seconds deficiency for a fork has nothing to recommend it; it ignores the very wide differences in the rate of decrement of forks, which will frequently cause errors of 200 or 300 per cent. in such estimations. The fractional expression is only slightly more accurate. It takes no account of the initial amplitude of vibration of the fork, which varies widely even in the same fork, and much more so in different forks. Moreover, since decrement is logarithmic, such a time fraction conveys a totally wrong picture of the hearing power. Attempts have been made to overcome some of these defects by the production of forks giving universal and constant initial intensity (by mechanical strikers, etc.), and with universal similar decrement. In neither object has success been obtained, and it is extremely improbable that future attempts will meet with any more success.*

Gradenigo, in 1899,[34] devised some optical forks on which it was possible to observe the amplitude of vibration at any time during the fork's vibration; but the units were arbitrary, the gradations extremely rough, and the value confined to forks of low frequency. Bezold and Edelmann, in 1898,[35] published a paper in which they described an instrument for the graphic recording of the curve of decrement of vibration of tuning-forks. Their results were obtained from forks covering the lower two and a half octaves (16 to 96 d.vs. per second), and they claimed that such a curve would be applicable to all tuning-forks of the higher pitches.. Schmiegelow,[36] in the following year, criticised their results and conclusions; he suggested the construction of a curve on a distance basis for each fork, and expressed his results on a relative intensity basis. He constructed his curves by a number of experiments and rather disparaged the law of logarithmic decrement. Harvey Fletcher [24] has recently suggested the expression of tuning-fork results in terms of sensation units, calculated from the seconds deficiency.

* Bezold [21] stated that such attempts at the production of forks with standard initial intensity and standard decrement could only result in the production of inferior forks.

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Hearing Tests

Holding, as stated in the first part of this section, that the most rational and convenient way of expressing hearing power is in terms of percentage retention of normal hearing distance, and since tuning-forks may readily provide information on such a basis, I shall outline this practice and the mathematical considerations underlying it. The hearing is tested in the usual way, the duration of after-perception of a tuning-fork by a normal ear after perception by the patient has ceased being noted in seconds (seconds of deficiency). By reference to a table this figure is then translated into percentage retention of normal hearing distance. Such a figure is of course open to comparison, and will be identical with the findings for the patient by other forks or instruments of the same pitch. The table referred to would be supplied by the makers of the fork at the time of purchase; if not, it can be readily drawn up at the expense of a little time, with the aid of a few experiments and a little practice in mathematics. Or the standardisation of existing forks might be determined by a central institute, for what need only be a small fee. Where one contents oneself with quantitative estimation for a single pitch, reference to such a small printed table will be most convenient; where one performs complete quantitative testing for a range of forks, a graph recorder, as suggested by Lowndes Yates, is conveniently employed.*

This use of tuning-forks has been objected to on the ground that it introduces a second personal factor; this is so, but its importance can easily be exaggerated, as very little practice enables one to speak with confidence as to the end-point of perception of a fork. It cannot, of course, be denied that such tests are impracticable for examiners who suffer from deafness of varying degree. A constant degree of deafness can to some extent be compensated. Those who cannot thus circumvent their handicap must either rely upon costly and cumbersome audiometers, or employ their secretary as "*corpus vile.*"

Selection of tuning-forks for these tests, while by no means essential, can do much to facilitate their carrying out. The lower forks should be as free from overtones as possible and should have a fairly rapid rate of decrement. All low forks have a slow (distance) decrement, and if this is at all exaggerated testing may be very tedious. The higher forks should be of

* I must gratefully acknowledge that I have been much helped by this author's paper,[37] and stimulated by his conversation.

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good quality; overtones, if present, may not be perceived by the examiner and may rob any result of value. These higher forks (*e.g.* 512 d.vs. and over) should have as slow a decrement as possible, for the greater accuracy obtained more than compensates any extra time taken in testing.

While the translation of results from seconds deficiency for any fork to percentage N.H.D. is for the otologist merely a matter of referring to a table and requiring no mathematical knowledge, it is of interest to discuss the mathematical and physical basis underlying the obtaining of such results, and the circumstances producing them.

The Physical Basis of Tuning-fork Quantitative Tests.—(*A*) The fundamental basis of these tests rests upon the "law of logarithmic decrement," governing bodies in free vibration. Tuning-forks, except when their vibrations are forced, or of unnaturally great amplitude, conform to it. It is expressed—

$$\frac{A1}{A2} = \frac{A2}{A3} = C$$

where A1, A2, A3 are successive amplitudes of vibration after equal time intervals.

(*B*) Since the distance at which a sound is audible varies directly with (but as the square root of) the amplitude of vibration of a body, this formula can be expressed in distance terms—

$$\frac{D1}{D2} = \frac{D2}{D3} = C$$

where D1, D2, D3 are successive distances at which the fork is audible after equal time intervals.

This may be clearer if expressed

$$D1 \div C = D2,\ D2 \div C = D3, \text{ and obviously } DD1 \div C^2 = 3.$$

Further, suppose that in this case the time interval was t seconds, the "decrement factor" (distance) for this period was C; for twice the time interval (audibility changing from D1 to D3) it is C^2.

now for t seconds the factor is		C
for $2t$	,,	C^2
therefore for 1 second	,,	$t\sqrt{C}$
and for n seconds	,,	$t\sqrt{C^n}$.

(*C*) Mention has been made of hearing distances, and this requires qualification. Hearing distance is obviously the distance from a sounding body to the receptive point of hearing; this is equal to the distance from the source of sound to the tragus plus the distance from the tragus to the receptive

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point of hearing. This latter distance is functionally decidedly less than the anatomical length of the meatus; one can explain this according to one's beliefs by saying that in the meatus one is dealing with conduction in a closed tube, or by saying that the function of the meatus is primarily by resonance and only secondarily by conduction.

The determination of this functional length of the meatus is easy from the formula $D1/D2 = D2/D3$; it was discussed in Lowndes Yates'[37] recent paper, and his finding of $\frac{1}{2}$ in. agrees closely with mine. Schmiegelow[36] made the distance slightly more. Throughout this paper, as should be the usual practice, hearing distance therefore means the distance from the sounding object to the tragus, *plus* $\frac{1}{2}$ in.

(*D*) It is a simple matter to determine the "factor of decrement" (distance) for a fork, but accuracy will depend upon averaging a number of results. Hold a fork at a distance D1 from the ear; when no longer perceptible, approach it to D2; it is audible for *t* seconds. Then the factor for an interval of *t* seconds = D1/D2, and is a constant for the fork. For 1 second the factor equals $t\sqrt{D1/D2}$. We will in future call this constant factor of decrement for an interval of 1 second—K.

(*E*) Now $D1 \times K = D2$ (for an interval of 1 second, K being the factor for 1 second, and D2 being the distance at which audibility ceased 1 second before ceasing at D1).

$D1 \times K^2 = D3$ (interval of 2 seconds), etc. Therefore, having previously calculated K, and knowing D1, we can determine the distance at which the fork was audible any number of seconds before it ceased to be audible at D1, *e.g.*, *n* seconds before ceasing to be audible at D1 it was audible at $D1 \times K^n$. We can therefore express the hearing power for any number of seconds deficiency (as compared with the normal) as the fraction

$\frac{D1}{D1 \times K^n}$ or, cancelling out, $\frac{1}{K^n}$, *n* being the number of seconds deficiency.

(*F*) It has been said that hearing power is best expressed, not as a fraction, but as percentage retention of normal hearing distance. Thus, for *n* seconds deficiency it would be:—

$\frac{D1 \times 100}{D1 \times K^n}$ or, cancelling out, $\frac{100}{K^n}$ per cent. N.H.D.

I have nowhere met a formula so simple for this expression.

By giving *n* different values we can readily draw up a table covering the whole period of vibration of the fork.

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Quantitative Estimation of Perceptive Function.

I have suggested in an earlier section that all tests of bone conduction should be of absolute bone conduction, and I believe that quantitative determination of bone conduction can afford valuable information as to perceptive function.

One cannot obtain the same accuracy in testing absolute bone conduction as in testing by air conduction owing to the greater difficulty in determining the end-point of perception. The value of quantitative testing of bone conduction is confined to pitches between 128 and 1024 d.vs. per second; the 128 fork is on the border-line of reliability, as its end-point is sometimes impossible to determine. Great accuracy being impossible, importance cannot be attached to small variations. In testing duration of perception of tuning-forks by bone conduction, attention must be paid to auditory fatigue, which occurs readily in this form of testing, much more readily in some cases than in others. It is advisable to lift and replace the tuning-fork, rather than to keep it in constant apposition to the mastoid.

The efficiency of contact between the tuning-fork base and the bony skull plays a large part in determining the amount of perception in this test. Doubtless the application of the tuning-fork to the teeth, with the intermediation of some modified dental prop, would best overcome this source of error; but I believe that with very little practice one learns to use a fairly constant degree of pressure, reducing the error to negligible proportions. Lake and Peters,[38] however, did not think so, and they devised a spring device for attachment to the stem of the fork.

In the normal ear, using tuning-forks (*i.e.*, prongs for testing air conduction, stem for bone conduction), perception by air conduction always exceeds perception by absolute bone conduction, and the two bear a constant ratio to each other. With the forks I have used I find, by calculation, that when perception by absolute bone conduction ceases, the fork is audible if held half an inch from the tragus, that is, at one inch hearing distance. This applies approximately to the 128, 256 and 512 forks. The 1024 fork is audible similarly at one and a half inches hearing distance.* It may then be said for these forks

* When testing bone conduction the fork is at the minimum distance; in testing air conduction the minimum distance is the length of the meatus, or $\frac{1}{2}$-in. If then when perception by absolute bone conduction ceases the fork is audible by air conduction at 1 in., absolute bone conduction corresponds to a hearing power in terms of hearing distance of $\frac{1}{2}/1$, or 50 per cent. N.H.D.

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that normal absolute bone conduction equals approximately, for the first three, 50 per cent. N.H.D., and for the last, 33 per cent. N.H.D. The actual figures are: C, 49 per cent.; C1, 54 per cent.; C2, 50 per cent.; C3, 32 per cent. N.H.D. While more work on this point is required, and while the figures will probably vary according to the construction of the forks, such figures should supply a fair average for the relationship.

It may at first seem unnecessarily complicated to express absolute bone conduction in terms of air conduction, but it is rational and has the advantage of making any alteration in the relation of the two immediately apparent. In testing a patient one observes the end-point of his perception by absolute bone conduction, and then determines how many seconds longer it is perceptible by normal absolute bone conduction. Such seconds deficiency absolute bone conduction are not comparable to seconds deficiency air conduction, for the application of the tuning-fork base to the mastoid entails resonance of the cranial structures with consequent more rapid decrement of the fork's vibration. This increase in decrement is readily determined for each fork with sufficient accuracy for all ordinary purposes. The method of its determination is best explained by an example.

Example.—Suppose one takes a fork for which it has been determined that, after ceasing to be audible at 3 in. distance under normal conditions of damping, it is audible at the tragus for a further 50 seconds. Hold the fork at 3 in. distance, and as soon as it ceases to be perceptible place the base on the mastoid and test absolute bone conduction; suppose it is audible by A.B.C. for 20 seconds; immediately perception by A.B.C. ceases, remove the fork and hold the prongs to the tragus, testing A.C.; suppose it is further audible here for a period of 20 seconds.

Normally, as stated, the fork after ceasing to be audible at 3 in. would have been audible at the tragus for a further 50 seconds; actually it was audible for 40 seconds (20 testing A.B.C. plus 20 testing A.C.); obviously the increased rate of loss must have occurred while A.B.C. was being tested; then it lost in 20 seconds testing of A.B.C. what it would have lost in 30 seconds of A.C. This may be expressed for the fork as A.B.C. : A.C. = 20 : 30 = 1 : 1·5. Then for this fork, if A.B.C. seconds deficiency is to be comparable to A.C. seconds deficiency, 5 seconds must be added to every 10 seconds A.B.C. deficiency.

It is of course not essential to compare the patient's

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absolute bone conduction with the normal absolute bone conduction; instead, its seconds deficiency as compared with the normal perception by air conduction may be determined, the interval between the normal air conduction and normal absolute bone conduction being known. The results so obtained for absolute bone conduction are ready for direct comparison with the results of the tests of air conduction, and by reference to the same table are translated into percentages N.H.D. This is readily graphed, or the result may be expressed as the fraction :—

$$\frac{\text{Patient's A.B.C. as percentage N.H.D.}}{\text{Normal A.B.C. as percentage N.H.D.}}$$

This is rational, for it gives the normal A.B.C. a value of 1, and the minimum A.B.C. a value directly proportional to the maximum intensity of the fork—the maximum degree of deafness which we are justified in assuming as the result of any test.

In this paper I have outlined methods by which we can accurately assess the total hearing power (A.C.) and the perceptive function (A.B.C.); from which data the condition of the conductive apparatus can at once be deduced. The results are expressed on a real and intelligible basis and are comparable, wherever and by whomever obtained. They can be expressed in graphic form and, if necessary, an accurate picture of the hearing power throughout the pitch range can be presented. While no necessary part of the method, I believe that such full testing, carried out as a routine, would result in some reorganisation of ideas and the general improvement of otology.

The paper has attempted to cover rather a wide range and, in order to clarify its important parts, I shall conclude by describing my method of functional examination and by figuring a typical "decrement table."

Examination.

I test the hearing distance for the watch (N.H.D. according to conditions at time of testing). If this is not heard or the distance is small, I test with the acoumeter (N.H.D. = 40 feet, or *c.* 500 inches).

I then instruct the patient to occlude both meatus, and then place a vibrating tuning-fork above the glabella; if there is any lateralisation of perception I know that there is unilateral,

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or unequal bilateral, perceptive deafness. (This test, lateralisation of absolute bone conduction, might be useful to the neurologist, whose chief anxiety is a unilateral nerve deafness.)

I then hold a fork (preferably 256) close to the tragus and, when perception ceases, transfer the base to the mastoid, occluding the meatus, preferably by pressure on the tragus with a finger of the other hand (if he hears it he has conductive disorder); on this perception ceasing I immediately see if I have any further perception by absolute bone conduction; if I have, the patient has some additional perceptive deafness.

TABLE III.

Fork 512 d.vs. . . . . Mark A.

Factor 0·052.

Seconds Deficiency.	A.C. per cent.	A.B.C.
0	100·0	50/50
1	95·0	...
3	86·0	41·0
5	77·0	38·0
7	70·0	34·0
10	60·0	28·0
15	46·0	20·0
20	36·0	16·0
25	28·0	11·0
30	22·0	8·0
35	17·0	6·0
40	13·0	5·0
45	10·0	4·0
50	7·8	2·5
60	4·7	1·3/50
70	2·8	...
80	1·7	...
90	1·0	...

B.C. : A.C. = 1 : 1·2.
A.B.C. = −13 seconds or 50 per cent. N.H.D.
R.B.C. = −27 seconds or 25 per cent. N.H.D.

Quantitative estimations for the two ears may be performed at the same test, but A.C. and A.B.C. are best tested separately. All the necessary particulars are in the table of reference (Decrement Table).

I then test with the C 5 fork, and usually test the upper limit (monochord A.C. and B.C.) and the lower limit. Such testing only occupies four or five minutes. If complete investigation is required, I then proceed to do quantitative tests for all the C forks (C—1 to C 5, by A.C., C—1 to C 3 for A.B.C.).

Such complete examination of a case, with production of graphic records, occupies about twenty minutes.

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