THE CLINICAL DETECTION OF AUDITORY RECRUITMENT

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Introduction

The clinical detection of recruitment has aroused considerable interest because of its value in distinguishing nerve deafness from middle-ear deafness, and because it measures hearing ability over a range of intensity well above threshold. A discussion of its diagnostic applications will be found at the end of this paper.

Many different recruitment tests have been developed but interest in this subject is so recent that there has been little opportunity to establish their reliability and to find out more about the phenomenon. An earlier article4 gave a brief description of recruitment, of the established methods of recruitment testing, and of some of the newer tests under development. Recent research has proved the validity of some of these newer tests which have been developed into short, reliable tests, easy to carry out clinically.

The purpose of this paper is: (1) to describe the recruitment phenomenon, (2) to explain the principles of recruitment testing, (3) to describe the test methods in use, (4) to describe some controlled experiments on one of the recruitment tests developed by the authors, (5) to point out some pitfalls in recruitment testing, (6) to compare the relative merits of the various test methods, and finally (7) to discuss the clinical uses of recruitment testing.

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Description of recruitment phenomenon

Before attempting a more detailed description of recruitment we must define the often confused terms "intensity" and "loudness". "Intensity" refers to the magnitude of the sound wave reaching the ear, whilst "loudness" is a measure of the sensation experienced by the listener whose ear is stimulated by that sound wave. Thus "intensity" is a physical property of the sound wave in air, whilst "loudness" refers to a subjective sensation. Intensity and loudness are not identical. For instance, sounds of quite different intensity are required to reach the thresholds of a deaf and a normal listener and yet give rise to sensations of equal loudness. Even in a normal listener, two sounds of equal intensity and different frequency may be deemed to be of different loudnesses.

The loudness with which a sound of given intensity is perceived provides a measure of the sensitivity of that ear. Recruitment is said to be present when the sensitivity of an ear is subnormal at low intensities but more nearly normal at higher intensities. Thus in a normal and in a recruiting deaf ear the sensations of loudness aroused by a sound of low intensity will differ markedly; but the loudness sensations will be equal in the two ears for sounds of much higher intensity. Further, in a non-recruiting deaf ear and in a recruiting deaf ear the loudness sensations aroused by a sound of low intensity, but will differ markedly for sounds of high intensity. Thus change of sensitivity may be better understood after consideration of the following experiment.

Two sounds are presented to a listener, first one to one ear, and then the other to the opposite ear. The listener is asked to adjust the intensity of the second sound until it appears to be of equal loudness to the first one. This process is repeated at a number of intensity levels and the pairs of intensities which sound equally loud in the two ears are plotted along the X and Y axes of a graph. If both ears of the listener are normal, the points plotted will lie along a straight line inclined at 45° to each axis, because sounds of equal intensity will appear equally loud in the two ears. This is line AB in Fig 1. The same experiment can be repeated with a listener who has one normal ear and one ear deaf and not showing recruitment. To reach threshold in the two ears, the intensity presented to the deaf ear must be greater than that fed to the good ear by the amount of the hearing loss (AC in Fig. 1). Similarly at higher intensities the two sounds will appear equally loud when the sound intensity in the bad ear is greater than that in the good ear by the amount of the threshold hearing loss. Therefore, the corresponding graph will be a straight line, CD in Fig. 1, parallel to the "normal" graph but displaced from it by a distance corresponding to the threshold hearing loss. The same experiment can be repeated on a person with one good ear and one deaf ear which does show recruitment and which has the same threshold hearing loss as in the previous case. As before, to reach threshold in the two ears, the sound...
intensity in the bad ear will be greater than that in the good ear by the amount of the threshold hearing loss. But as the sound intensity is increased, by definition of recruitment, the sensitivity of the deaf ear becomes more normal; and at the higher intensity E (Fig. 1), its sensitivity is normal and sounds of equal intensity will appear equally loud in the normal and the deaf ear. The sensitivity of the deaf ear approaches normal gradually as the intensity is increased and therefore the corresponding equal loudness graph will be line CB of Fig. 1. Curve CB passes from CD, representing subnormal loudness sensitivity, towards AB, representing normal sensitivity and thus shows graphically the variation of sensitivity with change of intensity, which is the essence of recruitment. The graph also shows that loudness in the recruiting ear increases relatively rapidly as the intensity is changed from C to E. This rapid increase of loudness with increase of intensity will be referred to later, when the methods of recruitment testing are discussed.

**Principles of recruitment testing and test methods in use**

All methods for the detection of recruitment are based on investigating, in the ear under test, the change of loudness with change of intensity. This is achieved either by comparing the intensities producing equal loudness in normal and abnormal ears, as in Fig. 1, or by measuring the intensity
difference limen for loudness (for explanation see later). Accordingly recruitment tests can be divided into two groups:

1. Loudness balance tests.
2. Difference limen tests.

Loudness balance tests. The loudness balance tests where two sensations, one of them normal and the other subnormal, are to be matched, are obviously suitable only for subjects who have normal hearing in one ear for sounds of at least one frequency, because the sensations experienced by two different individuals cannot be compared.

The earliest loudness balance test method, in fact the first recruitment test of any kind, was the alternate binaural loudness balance test described by Fowler in 1936.1 The test is carried out by balancing the loudness of a sound heard in the bad ear against the loudness of a sound of the same frequency in the opposite ear, where hearing is normal, in exactly the same way as described in connection with Fig. 1. Fowler displayed his results by joining the points corresponding to those intensities which were heard with equal loudness in the normal and deafened ears. This method is shown in Fig. 2. Fig. 2a and 2b shows the results obtained with recruiting and non-recruiting ears respectively. An alternative method of displaying the same result is shown in Fig. 1; it was introduced by Steinberg and Gardner in their exhaustive paper on recruitment published in 1937.2

When both ears are deaf for the frequency at which recruitment is to be tested for, it is possible to balance the loudness of a sound at this frequency against the loudness of a sound at a different frequency for which hearing is normal. This test is the bifrequency loudness balance test, which can be carried out either with the test and comparison sounds in the same ear or in opposite ears. But sounds of different frequencies and of equal intensities do not necessarily sound equally loud even in normal ears. Therefore, in the bifrequency tests the results have to be corrected according to the Fletcher and Munson equal loudness contours3 which show the normal relation between the intensities of sounds of different frequencies perceived to be of equal loudness. The construction of the necessary correction chart is fully described in an earlier paper.4 Patients find no difficulty in making the necessary loudness judgments, unless the frequencies of the two sounds to be balanced are very different (more than 2½ octaves apart). The patients will at first be diffident about the correctness of their judgment, but in fact they will give very consistent results. The tests are easy to carry out and well within the scope of the operator who obtains the standard threshold audiogram.

As described in a previous paper4, patients frequently experience difficulty in balancing the loudnesses of two sounds heard simultaneously in the two ears and prefer a test where only one sound is to be heard at any given time.
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**FIG. 2A.**

**FIG. 2B.**

Rt. ear = X --- X  
Lt. ear = O --- O.
Another variant of the loudness balance technique is that developed by De Bruine-Altes\textsuperscript{5}. Her method consists of finding the intensity of sound at a given frequency required to mask a sound of a different frequency. This measurement is repeated at a number of intensity levels. The test is so arranged that hearing for one of the two sounds, the masked or the masking sound, is normal and for the other abnormal. The results are compared with those obtained with normal persons, that is, when both masked and masking sounds are heard normally. In effect, the loudness of the masked sound is balanced against the loudness, or the masking effect, of the other sound. The advantage of the method is that the question presented to the patient is similar to that of a threshold test: he has to say when he begins to hear a test sound over and above the masking sound; in the other loudness balance tests he has to decide when two sounds are equally loud. It may be felt that the threshold type of test is easier than the balance type of test. But the consistency of results obtained with the ordinary loudness balance test show that there is, in practice, no difficulty in obtaining reliable readings. The disadvantage of the De Bruine-Altes’ test is that it requires rather laborious preparations.

\textit{Difference limen tests.} The second group of recruitment testing techniques is based on the measurement of the rate of change of loudness with change of intensity. It will be seen from Fig. 3 (an elaboration of Fig. 1) that the loudness increases with increase of intensity more quickly when recruitment is present than when it is absent. An intensity increase \(A\) to \(E\) is required in a non-recruiting ear to bring about the same change of loudness as is brought about by the much smaller increase of intensity \(C\) to \(E\) in a recruiting ear. Or again, assume that an increase of intensity \(a'\) to \(b'\) (Fig. 3) of the sound applied to the first (normal) ear has caused a given change of loudness in that ear. Then when the second ear is normal, or deaf and not recruiting, the same given change of loudness will be brought about by an intensity change \(a\) to \(c\), or \(g\) to \(h\), respectively (Fig. 3). If the second ear is deaf and showing recruitment, then the same given change of loudness will be brought about by an intensity change \(d\) to \(f\) (Fig. 3). The intensity change \(g\) to \(h\) equals \(a\) to \(c\), and is greater than \(d\) to \(f\). It is known that when the intensity of a sound is increased continuously, the corresponding loudness sensation does not increase continuously but in discrete steps. The intensity change sufficient to produce a just perceptible change of loudness is called the intensity difference limen for loudness. Assuming that in Fig. 3 the intensity change \(a'\) to \(b'\) is such that it produces a just perceptible change of loudness in the first ear, then intensity changes \(a\) to \(c\), \(g\) to \(h\), and \(d\) to \(f\) will also produce just perceptible changes of loudness in normal, non-recruiting deaf, and recruiting deaf ears respectively. These intensity changes, \(a\) to \(c\), \(g\) to \(h\), and \(d\) to \(f\) are the intensity difference limina for loudness of
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the various ears, and for the particular sound considered. Fig. 3 shows that as long as the slope of the equal loudness curve of the recruiting ear is greater than that of the non-recruiting ear, the difference limen, \( d \) to \( f \), of the recruiting ear is smaller than that of a normal, \( a \) to \( c \), or of a non-recruiting deaf ear, \( g \) to \( h \) (\( = a \) to \( c \)). Therefore, the presence or absence of recruitment can be determined by measuring the size of the loudness difference limen of the deaf ear and comparing this result with the known values obtained with normal ears. This principle is the basis of the test techniques used by Békésy, Luscher and Zwislocki, and by the authors of this paper.

Békésy’s recruitment test. Békésy’s recruitment tester\(^6\) measures the intensity difference limen for loudness at the threshold of hearing. It consists of an audiometer in which an electric motor controlling the attenuator increases or decreases, in two-decibel steps, the intensity of sound delivered to the ear, according to whether a key is pressed or not. The patient presses the key, and thereby increases the sound intensity gradually until his threshold of hearing is reached. When he hears the sound he releases the key, thus causing the sound intensity to decrease again. When he ceases to hear the sound he presses the key again, and so on. Thus the intensity of the test sound fluctuates between just above and just below threshold. Another motor varies the frequency of the
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test sound continuously, taking about 15 minutes to cover the range of 100 c.p.s. to 10,000 c.p.s., and the instrument records on a chart the fluctuations of intensity over that frequency range. Typical completed charts are drawn in Fig. 4. The instrument, therefore, records graphically the intensity difference limina for loudness at threshold. According to the theories outlined above, the size of the difference limen should be an indication of the presence or absence of recruitment; when the difference

limen is smaller than normal, recruitment is present; when the same size as normal, recruitment is absent. Fig. 4a, and 4b, shows quite clearly the different results obtained when recruitment is present and absent respectively.

The advantages of this method are that it is completely automatic and very simple to carry out, and pure tone audiogram and recruitment test results are determined simultaneously. It is a monaural test and, in contrast with the loudness balance tests, normal hearing at at least one frequency is no necessity (but, as will be shown later, it is desirable).
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A disadvantage of the method is that the absolute size of the difference limina thus determined is assumed to indicate the presence or absence of recruitment. But patients will vary in the time they take to react to a change of loudness and to depress or release the operative button; their sense of rhythm will affect their performance, and the fatigue effect of listening to near-threshold sounds may considerably alter the reaction time of an individual between the start and finish of a complete test; and even in normal ears the size of the loudness difference limen varies from frequency to frequency near the threshold of hearing. For these and other reasons, therefore, the absolute size of the intensity difference limen determined by this method is not always a good indication of the presence or absence of recruitment in untrained listeners.

The Lüscher and Zwislocki recruitment test. A similar test carried out well above threshold and at selected discrete frequencies is that described by Lüscher and Zwislocki. In this test, the intensity of output of an audiometer is varied automatically and continuously between an upper and a lower limit at a fixed rate of about two complete cycles of intensity variations per second. The size of these variations is expressed as a percentage of the mean intensity (called the "percentage modulation"). A mechanical control allows this percentage to be varied from zero to about 60 per cent. The percentage modulation at which the patient begins to hear variations of loudness is called the "critical percentage modulation," and is taken as a measure of the intensity difference limen. According to theory, if this difference limen is smaller than normal, then recruitment is present, if it is normal, then recruitment is absent. The test is usually carried out at 40 db. above threshold because the normal difference limen at this sensation level is practically independent of frequency. By using this test procedure, 10-16 per cent. was found to be the range of normal difference limina, whilst persons known to have recruiting deafness gave results of 8 per cent and less. Therefore, all deaf ears with a critical percentage modulation of more than about 8 per cent. are considered to be non-recruiting, whilst those showing a critical percentage of less than 8 per cent. are considered to be recruiting. This test is quick and simple, and can be performed on any patient, even if hearing is abnormal in both ears over the whole of the audio frequency spectrum. But a number of factors reduce the reliability of the test, so that recruiting deaf patients may, when tested by this method, show critical percentage modulations that are larger than the deciding 8 per cent., and normal people may be able to detect fluctuations that are smaller than 8 per cent. Thus, Lüscher and Zwislocki state that even in the presence of recruitment, the critical percentage modulation may not fall below 8 per cent. if the hearing loss is less than 30 db. or if the threshold audiogram does not show a steep fall. They also state that with practice the critical percentage modulation may decrease to 8 per cent.
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even when hearing is normal. In our opinion individual differences of judgment may well be another source of uncertainty. These drawbacks are certainly confirmed by the small number of tests carried out by the authors with such a recruitment tester. Another point that should be weighed against the reliability of this test is the probability that it really measures a difference limen for quality rather than the intensity difference limen for loudness. It is possible that future experiments will show that there is indeed a correlation between recruitment and the size of such a difference limen for quality, but this is, as yet, an unestablished theory. Moreover, the theoretical justification of the test could not easily be based on the theory underlying the relationship between recruitment and difference limen discussed earlier, as the latter is confined to intensity difference limina for loudness.

*Difference limina for loudness, pitch and quality.* As explained in the introduction to this paper, the characteristics of the sound stimulus and of the resulting subjective sensation must be kept separate.

Thus "intensity", "frequency" and "complexity" describe the physical characteristics of the sound waves stimulating the ear. The "complexity" of a sound wave is determined by the relative frequencies and intensities of the sinusoidal components which, integrated, give the sound stimulus considered as resultant; or more descriptively, "complexity" is the extent to which the wave shape of the sound wave differs from sinusoidal. As the complexity of the sound stimulus is increased, the basilar membrane is stimulated at an increasing number of points, each point corresponding to a sinusoidal component. In the subjective field, "loudness", "pitch", and "quality" are the characteristics of auditory sensations. For the purpose of this discussion, quality can be defined as that characteristic of the sensation which is neither loudness nor pitch, or as the "degree of purity" of the sound perceived. A change in any one of the characteristics of the stimulus (intensity, frequency, or complexity) will potentially affect all the subjective characteristics (loudness, pitch, and quality). But the intensity-loudness, frequency-pitch and complexity-quality relations will generally be the most obvious. The change of intensity that produces a just perceptible change in loudness, pitch, or quality, is the intensity difference limen for loudness, pitch, or quality, respectively. Similarly, there are frequency and complexity difference limina for loudness, pitch, and quality.

Now in the Lüscher and Zwislocki test, a sound of pulsating intensity is used. The mathematical representation of the intensities of a sound of pulsating intensity can be written as

\[ i = I(t + M \sin 2 \pi f_s t) \sin 2 \pi f_t t \]

which can easily be shown to be equivalent to

\[ i = Is \sin 2 \pi f_t t + \frac{IM}{2} \cos 2 \pi (f_s - f_t) t - \frac{IM}{2} \cos 2 \pi (f_s + f_t) t \]
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where \( i \) = instantaneous intensity of test sound
\( I \) = mean intensity of test sound = intensity when there is no modulation.
\( M \) = percentage modulation
\( f_1 \) = frequency of test sound
\( f_2 \) = frequency of intensity pulsations (about 2 c.p.s.)
\( t \) = time.

The second equation shows that a sound of pulsating intensity is equivalent to the sum of three sinusoidal sounds of frequencies \( f_1 \), \( f_1 - f_2 \), and \( f_1 + f_2 \). The process of modulation leaves the intensity of the component of frequency \( f_1 \) (the sound being modulated) unaffected and introduces components of frequencies \( f_1 - f_2 \) and \( f_1 + f_2 \), called the sidebands, whose amplitude increases from zero as the percentage modulation is increased from zero. Therefore, increasing the amplitude of the intensity pulsations of a “sinusoidal” sound stimulus means increased complexity of stimulus. The ear should be able to appreciate the changes in complexity as long as the differences in frequency and intensity between the components involved are not smaller than the frequency-pitch and intensity-loudness difference limina. In fact, both these limina are just equal to or smaller than the differences between the components involved in the cases quoted by Lüscher and Zwislocki:

\[
\Delta f = 2.5 \text{ c.p.s. at 1000 c.p.s. and 40db sensation level (according to "Hearing" by Stevens and Davis),}
\]

\[
f_1 - f_2 = 2 \text{ c.p.s. } 2(f_1 - f_2) = 4 \text{ c.p.s. (Lüscher),}
\]

\[
\Delta I = 0.75 \text{ db.} = 9 \text{ p.c. intensity change (according to "Hearing" by Stevens and Davis),}
\]

\[
M = \frac{10\%}{2} \text{ in terms of amplitudes } = \frac{21\%}{2} \text{ in terms of intensity (Lüscher).}
\]

These calculations assume that the intensity pulsations are sinusoidal. If the intensity pulsates by sudden jumps then the increase in complexity of the sound stimulus is even greater. Of course, the individual elements of the basilar membrane are not infinitely selective and therefore the sidebands will also excite the receptor which would ideally respond only to the component of frequency \( f_1 \). The interference of the components of frequencies \( f_1 \), \( f_1 - f_2 \) and \( f_1 + f_2 \) in this receptor element will cause an amplitude fluctuation of frequency \( f_2 \). The amplitude of these fluctuations will be less than it would be if all the energy of the sidebands excited this one receptor. The just perceptible change of sensation which serves as the unit of measurement in the Lüscher and Zwislocki test is therefore a combination of changes of quality and loudness produced by variations in the complexity and intensity of the stimulation of the basilar membrane.

A new technique for the detection of recruitment. Another recruitment
test based on the difference limen principle and which has shown itself to be reliable after numerous tests is that developed by the authors of this paper. (The test will be referred to as the "DL Test".)

In this test, the intensity difference limen for loudness is found by applying two sounds of the same frequency to the same ear, one after the other, and measuring the intensity difference between those sounds that are heard to be just perceptibly different in loudness. The difference limen is determined in this manner at two different intensity levels. If the difference limen increases or remains unchanged with increase of intensity, then recruitment is present; if it decreases with increase of intensity, then recruitment is absent. The development of the test, the principles upon which it is based and the apparatus used for carrying it out, are described in the following paragraphs.

In the test the intensity difference for loudness is determined by switching two sounds, one after the other, to the ear to be tested. The intensity of the second sound is changed until it sounds just perceptibly less loud than the first sound. Then the intensity of the second sound is increased until it sounds just perceptibly louder than the first sound. The amount by which the intensity of the second sound had to be altered, to change it from being just perceptibly less loud to just perceptibly louder than the first sound, is a measure of the difference limen. This intensity change is in fact equal to twice the absolute value of the difference limen because two steps of loudness change are involved: 1. from less loud to equally loud; 2. from equally loud to louder. This value is easier to determine clinically, and its use does not invalidate the test, which is based upon the relative values of difference limina. The values shown in Fig. 5 for normal difference limina have been doubled to allow for this factor. According to the theory explained earlier, this difference limen should be smaller than normal when recruitment is present, and normal in size when recruitment is absent. However, when the method was tried out, it was found that although most cases bore out the theory there were some with recruiting deafness who showed difference limina of normal size, and some with normal hearing who had smaller than normal difference limina. This was considered to be due to variations of individual loudness judgments or of the attention paid to the test by the patient, etc., just as with the Békésy and Lüscher tests. To eliminate the effect of these individual variations on the reliability of the test it was necessary to make the results dependent on the relative value of a number of difference limen measurements, carried out on the same person under different conditions, rather than on the absolute value of the difference limen. It is well known that the normal intensity difference limen for loudness is relatively large at low sensation levels and much smaller at higher sensation levels. On the other hand, as was shown above, when recruitment is present the difference limen is much smaller than normal at low intensities and increases
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to normal values at higher intensities. The variation of the difference limen with sensation level for normal people is shown by the solid line and for recruitingly deaf subjects by the dotted lines in Fig. 5. To determine the way in which the difference limen changes with intensity, it was decided in the first place to measure the difference limen at three different sensation levels (4, 24, 44 db.). Experience showed that two measurements (at 4 and 44 db. sensation levels) are sufficient. If the difference limen decreases with increasing sensation level it is assumed that there is no recruitment. If the difference limen increases, or remains unchanged, with increasing sensation level then recruitment is present.

![Graph showing difference limen variation with sensation level](image)

Thus the variation of the value of the difference limen (a relative measurement) is taken as the deciding factor of the test rather than an absolute value, and indeed the tests described below show that the effects of individual variations of loudness judgment are largely eliminated. Other factors (duration of the two test tones and of the interval between them: shape of sound wave envelope (see Fig. 8) when switching on and off) which, if they are allowed to vary, will introduce a source of error into the test, are eliminated by standardization of the switching sequence. (See later.)

Description of the recruitment tester. The recruitment tester was primarily designed to detect recruitment by the DL test technique. But to establish, first, the validity of this test, the results had to be compared with those obtained by a loudness balance test carried out on the same patient. Therefore, the instrument was made in such a way that tests of both types could be carried out.
In each of these tests, the two sounds whose loudnesses are to be compared are fed one after the other to the appropriate ear. The intensities of the two sounds are controlled independently by separate attenuators. The duration of the two sounds and the time spacing between them, as well as the envelope of the wave during switching on and off, are standardized by the automatic switching action of the instrument. After the operator has pressed the initiating switch, an ordinary bell push, the instrument carries out the switching sequence without further action on the part of the operator. The switch also turns on indicator lights whilst the test sounds are switched on. A red light is visible while the first sound is on and a green light while the second sound is on. The patient identifies the sounds by referring to the colour of the indicator light which he sees while he hears the sound. Many patients find this easier than referring to "first sound" and "second sound" or to "right ear" and "left ear". The various controls are also called red or green, depending on whether they control the "red" or "green" sounds respectively.

A schematic diagram of the instrument is shown in Fig. 6 and photographs in Figs. 7a and 7b.

The instrument consists of (1) two sinusoidal sound generators, (2) two independent signal channels, each channel containing an attenuator and an electronic switch controlled by the timing unit, and (3) the headphones. The switching is carried out by electronic switches which have no moving parts and are therefore noiseless in operation. (The alternative is to use mechanical relays which inevitably make a noise in operation.) In this way noises which will distract the patient's attention...
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are eliminated. In considering the action of this instrument the electronic switches can be regarded as ordinary on-off switches.

The sound generators are conventional electrical oscillators, the frequency of the output of each being adjustable independently to any one of seven fixed values (250, 500 c.p.s., 1, 2, 3, 4, 6 kc.p.s.). The difference limen and binaural loudness balance tests are carried out with sounds of one frequency at a time. Consequently only one sound source is required and therefore the output of one of the oscillators (A) is connected to both the red and the green signal channels simultaneously by putting the oscillator selector switch into the "A only" position (Fig. 6). With the selector switch in this position the second oscillator is inoperative. In the bifrequency loudness balance test two sounds of different frequency are to be compared. Therefore one of the oscillators is connected to the red channel and the other to the green channel by putting the oscillator selector switch into the "A and B" position. If the instrument had been designed for the difference limen test only, then the second oscillator and the oscillator selector switch would not have been necessary.

The electronic switches of each signal channel are normally switched off and no signal reaches the attenuators and headphones. When one of the switches is turned on, the output of the generator to which it is connected is fed to the corresponding attenuator. The attenuator then determines the intensity level of the sound that reaches the headphones. The switches are controlled by impulses from the timing unit (see Fig. 6). When the initiating switch is pressed the timing unit first switches the red electronic switch on for 1·7 seconds and then off; and 0·33 second after turning the red switch off, it turns the green switch on for 1·7 seconds and then off again. The duration and the manner of pressing the initiating switch have no effect on the switching cycles of the electronic switch. Each sound is turned on and off in such a way that a smooth wave envelope results, the intensity reaching its maximum value about 0·08 second after switching on, and zero intensity 0·08 second after switching off. 0·08 second was found to be the maximum permissible duration of the on or off switching. Increase above this value will allow the listener to detect a "build-up" and "fall-off" of the signal. The time taken for the signal to reach its maximum or zero amplitude after closing or opening the electronic switch must not be too short, in order to reduce the disturbing switching transients to a minimum. A photograph of the complete switching sequence is shown in Fig. 8, which represents the graph of test sound amplitude versus time. Finally, the headphone switch determines whether the sounds passed through the two signal channels are applied to the same or to opposite headphones. When the headphone switch is in the "monaural" position then both sounds go to the same headphone (see Fig. 6) as required for the difference limen and
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monaural bifrequency loudness balance tests. When the headphone switch is in the "binaural" position the two channels feed opposite headphones, as required for the binaural loudness balance test.

Before the instrument was put into use its attenuators were calibrated by finding the threshold of hearing of a number of young adults (18-30 years old) with no history of aural disease. The mean of the attenuator readings for threshold at each frequency was taken as the value of normal threshold at those frequencies.

The instrument can be used as a normal pure tone threshold audiometer. The sound can be applied to the patient's ear for 1-second intervals by the automatic action just described. Alternatively, the timing unit can be made inoperative and the sound applied to either ear for any length of time by an extra switch. The sound is then still switched on and off smoothly without abruptness. In this case the instrument is identical with a standard pure tone threshold audiometer. The instrument in use at University College Hospital and actually shown does not have this extra switch incorporated, but a similar instrument in use in the Phonetics Laboratory, University College, London, has.

The test procedure. In carrying out the test, the "red" sound is used as the reference sound, that is, its intensity is set to the value at which the difference limen is to be determined or the level in the "good" ear at which the balancing is first to be carried out (in the loudness balance test).

In the difference limen test, the green attenuator is first set so that the green sound intensity is about 10 db. greater than the red one. The initiating switch is pressed and the two sounds, "red" and "green", are fed automatically one after the other to the ear under test. The patient is asked which sound he hears louder, red or green, or whether he hears them equally loud. With this adjustment he probably hears "green" louder. The green attenuator is then changed towards the setting of the red attenuator by a given step and the process repeated. In this manner the setting of the green attenuator is changed in equal steps until the patient says that he hears the two sounds equally loud. The same procedure is repeated starting with the "green" sound of intensity about 10 db. below that of the red sound. As explained before, the difference between the settings of the green attenuator for which the "green" sound is heard just perceptibly louder and fainter than the "red" sound is taken as a measure of the difference limen. The difference limen is measured at 4, (24), 44 db. above threshold.

The whole test takes about 5 to 10 minutes to complete. The test procedure is simple and is well within the grasp of an audiometrician. 90-95 per cent. of patients experience no difficulty in making the necessary loudness judgments.

The loudness balance tests are carried out using essentially the same
FIG. 7A.

FIG. 7B.
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technique as that described for the difference limen tests. The centre of
the range of green attenuator settings giving sensations of equal loudness
is taken as the intensity which produces a sensation of loudness equal to
that produced by the "red" sound. In all the above tests the patient
sits in such a position that he cannot see the controls.

Comparison of difference limen and loudness balance test results

In order to discover how far the DL Test could be relied upon to detect
recruitment in clinical practice, it was decided to test a number of people
by both the difference limen and the loudness balance tests. The results
shown were obtained with the first 35 patients seen at the Deafness
Clinic of University College Hospital whose hearing proved to be suitable
for both tests, plus a number of normal people. The difference limen
results (measured at three intensity levels in each person) are tabulated
in Tables 1 and 2. Table 1 gives the results of all those subjects who, on
the basis of the loudness balance test results, had recruiting deafness.
Table 2 shows the difference limen results of the normal people plus those
of the patients who showed no recruitment in their loudness balance
results.

<table>
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<tr>
<th>TABLE 1.</th>
<th>TABLE 2.</th>
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</thead>
<tbody>
<tr>
<td><strong>Cases showing recruitment on basis</strong></td>
<td><strong>Cases not showing recruitment on</strong></td>
</tr>
<tr>
<td>of loudness balance test.</td>
<td>of loudness balance test.</td>
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<tr>
<td><strong>Sensation levels (db.)</strong></td>
<td><strong>Sensation levels (db.)</strong></td>
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<td>2</td>
<td>11/2</td>
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<td>3</td>
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<td>4</td>
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<td>21/2</td>
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<td>6</td>
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<td>Mean value</td>
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obtained in pure tone threshold tests when testing an ear with a threshold much higher than that of the opposite ear.) This is most likely to occur in the various recruitment tests as they are tests carried out at intensity levels sometimes well above threshold, and, unless precautions are taken, in cases where the threshold of one ear is lower than or equal to that of the other ear, high intensity levels will be reached at which the sound fed to the deaf ear will be heard by both ears. As is well known, the disturbing effect of this transmitted sound is eliminated in the threshold audiometer test by masking the better ear.

To decide whether this transmitted sound does in fact affect the results of the recruitment test, past results were re-examined and a number of tests were carried out with and without masking in the better ear. It is better to consider the effect of this transmitted sound on the difference limen and loudness balance tests separately rather than together. In examining the past results of the loudness balance tests, quite a number of instances were found where discontinuities occurred which were always at intensity levels which put the intensity of the sound in the bad ear just about 40 to 50 db. above the threshold of the opposite and normal ear. This seemed to confirm the theory. In this connection it is worth mentioning that some patients state that the quality and/or pitch of the sound perceived in their recruiting ear is different from that observed in their good ear. Also some patients seem to be able to decide with which ear they are hearing a sound, whilst others

![Figure 9](https://example.com/figure9.png)
cannot. On the other hand, when the intensities applied to the two ears were converted to loudness levels using the loudness-intensity graph (Hearing, by Stevens and Davis, p. 118) then it was found that the loudness contributions of the sound transmitted to the opposite ear are very small compared with the loudness perceived in the bad ear at the same time. A number of experiments were carried out in which the normal loudness balance test was carried out, but with a masking sound applied to the good ear during those periods when the test sound was fed to the impaired ear under test. The limited number and the complexity of these tests precludes any definite conclusion, which will only be reached when a greater number of cases have been tested.

But in the case of the difference limen results the process is more clear cut. As long as the sound can be perceived in the ear which is not being tested, however small its loudness may be relative to that in the test ear then if the sound in the untested ear is increased by one loudness unit the total loudness perceived will also increase. This relation can reverse the result of the difference limen test. Thus when the difference limen in the untested ear (at the sensation level of the transmitted sound reaching it) is smaller than the difference limen of the test ear (at the sensation level...
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without masking in the untested ear. Without masking their difference limina decreased with increasing intensity, suggesting the absence of recruitment; but with masking the opposite change took place, indicating the presence of recruitment. The theory was thus confirmed in these cases which showed recruitment by the loudness balance test. As there was a possibility (when the untested ear was masked) that the increasing difference limen, indicating recruitment, might have been caused by some form of central masking, patients who were known to be free from recruitment were tested with a masking noise applied to the untested ear at an intensity strongly in excess of that required, but the values of the difference limina remained unchanged.

It is of interest to note that the loudness balance and the difference limen tests of the case discussed above (results shown in Figs. 9 and 10) were repeated several times on different days, and the corresponding points obtained on successive occasions agreed most accurately. It would, therefore, be unjustifiable to disregard a few "out of place" points and draw a straight non-recruiting graph as the average result of the loudness balance test. The loudness balance test with masking could unfortunately not be carried out on this patient, because by the time the equipment was modified to permit masking, the hearing in that ear had completely gone. His difference limen results, however, were amongst those which indicated absence of recruitment when the opposite ear was not masked, but which indicated the presence of recruitment when the normal ear was adequately masked.

It seems advisable, therefore, when carrying out difference limen tests, to mask the ear not being tested when the intensity of the test sound is more than about 50 to 60 db. above the threshold of the untested opposite ear.

Conclusions

The detection of recruitment has aroused considerable interest because of its diagnostic uses. It is a convenient way of separating most types of nerve deafness from middle-ear deafness. It can usefully replace the orthodox bone conduction threshold tests, particularly when a bone conduction threshold, i.e. a knowledge of cochlear reserve, is required for each ear separately. Obtaining bone conduction thresholds of each ear separately is a very delicate test, because of the narrow tolerance of the indispensable masking noise intensities. The difference limen recruitment test, on the other hand, permits the examination of each cochlea separately, and in the cases where masking is required, the masking intensity does not seem to be very critical. The test does, moreover, obviate the necessity for using the notoriously inaccurate bone conduction receiver.

The difference limen test is also one which examines the patient's
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of the test sound in that ear), then the difference limen result obtained will be nearer to that of the untested ear than of the test ear, unless masking is used. For instance, consider the difference limen test results and threshold audiogram shown in Fig. II. The threshold of the right ear is 35 db. below that of the left ear. At 45 db. above the right threshold the intensity in the right ear is 80 db. above the threshold of the left ear and therefore it can be assumed that the sensation level of the transmitted sound in the left ear, which is normal, is about 30 db. Now Table 2 shows that the difference limen in non-recruiting or normal ears at such sensation levels is on the average about 3 db. and never more than 5 db. Therefore, it is reasonable to assume that even though the difference limen in the right (impaired) ear on its own might rise to higher values than 4 db., which is its value at a 4 db. sensation level, under the influence of the smaller difference limen in the normal ear the combined difference limen, which is the value measured in the test, is nearer to the smaller of the two difference limina (2½ db.). A similar case might arise when both ears are recruitingly deaf and the difference limen in the worse ear is measured. In order to confirm or deny this hypothesis, a number of suitable patients were tested by the difference limen method with and
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hearing above threshold, and therefore gives more information than threshold audiometry about loss of sensitivity to the louder sounds normally encountered. Although there is no adequate evidence yet, it seems possible that recruiting deafness will prove to be strongly correlated with discrimination deafness. If such a relation could be proved, the somewhat shorter and less cumbersome recruitment test could be used in some cases where the speech audiometer is required at present.

Of the recruitment tests at our disposal, the loudness balance tests were developed first. They are, like most recruitment tests, easy to carry out, both for operator and for the patient. Their results are reliable and seldom ambiguous when carried out with care. They can, however, be used only when the patient has some normal hearing. The simplest is Fowler's binaural loudness balance test, which can be used when the patient's hearing is normal in one ear at the frequency at which the test is to be carried out. The bifrequency loudness balance test, for which normal hearing for sounds of one frequency in either ear is sufficient, is more cumbersome because reference has to be made to the Fletcher and Munson equal loudness charts before the results can be completed. Patients find it more difficult to carry out if the difference between the frequency at which hearing is normal and the frequency at which recruitment is to be detected is too great. De Bruine-Altes' method is also a bifrequency balance test but patients probably find it easier, because they have to determine the intensity at which the test sound is just perceptible over and above the masking sound, instead of having to balance the loudness of two sounds. The preparations for it are more difficult because separate masking level charts have to be prepared for all combinations of test tone and normal hearing frequencies.

All the difference limen recruitment tests have the advantage over the loudness balance tests that they can be carried out even if hearing is impaired at all frequencies in both ears. The Békésy and the Lüscher and Zwislocki tests rely on the measurement of the absolute value of the difference limen to detect recruitment, whilst the DL Test relies on a relative measurement by making difference limen measurements at two sensation levels, 4 and 44 db., and deciding on the presence or absence of recruitment on the basis of the variation of the value of the difference limen. This makes the test more reliable by eliminating the effects of many of the individual and spurious variations in loudness judgments. Within the scope of the reliability test described, the new technique described in this paper proved by far the most reliable, with the Békésy test second and the Lüscher and Zwislocki test third.

As explained earlier, the theoretical background of the Lüscher and Zwislocki test is probably quite sound but is as yet not proven conclusively. But it is by far the shortest of all the difference limen tests (if carried out at one frequency only) taking only 2 to 3 minutes, while the
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DL and Békésy tests take 5 to 10 minutes and 15 minutes respectively. The apparatus required by all these methods is not too complicated and can, if necessary, be used for determining pure tone thresholds. The test techniques are not difficult and can be carried out without difficulty by audiometrists used to standard pure tone threshold audiometry. The tests of which the authors have considerable personal experience, the various loudness balance tests and their own DL Test, offer no great difficulty to the patient, who may be diffident, but will still give consistent results.

The authors wish to express their thanks to Mr. Myles Formby, Dr. Dennis Fry, and to Mr. F. W. Watkyn-Thomas, for their encouragement in this work, and to Mrs. Wood for her assistance in carrying out the hearing tests.

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