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Can present day audiology really help in diagnosis? — An otologist's question

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THE question asked in the title of this lecture is apt, and one which I have been asked on many occasions. Therefore, I am glad of this opportunity to answer it both formally and at some length. The key words in the title are 'diagnosis' and 'otologist', and they were intended to convey two points. Firstly, that the scope of this presentation is restricted to the diagnostic role of audiology and to its practice in hospital or associated clinics in support of the otologist, as distinct from paedo-audiology which is concerned more with local health and educational authorities. I will, however, touch on some of the electrophysiological techniques of measurement used in support of conventional paedo-audiological assessment, as these have uses in the hospital type of audiology as well and the facilities for them may often be sited in Department of Health and Social Security (D.H.S.S.) establishments.

The second point derived from the key words is to stress that it is the otologist and not the audiologist who has responsibility for making the diagnosis, except perhaps in those occasional instances where the audiologist is medically qualified. On the other hand, any specialist investigation infers not only the performance of tests but also the freedom to select those tests most appropriate to the particular patient, their appropriateness often only becoming apparent as the examination itself proceeds. Thus, a concept of 'diagnostic strategy', described first by Davis in 1962 and elaborated more recently by Coles and Priede (1972*a*), with

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respect to the British practice of audiology, needs to be adopted if the best possible diagnostic advantage is to be gained from such investigations.

It is also true that the investigator is, or should be, the best person to interpret the results of his tests; although of course he is not, or should not be, the only person who can do so. He must, however, restrict his report to a statement of quantities carefully measured and of his assessment of the audiological evidence as to the site of lesion.

I think many otologists worry about the encroachment of audiology into otology more than they need. In fact, I have met few if any audiological scientists, in this country or overseas, who do not recognize and, as far as I know abide by, the unalterable fact that the otologist has the ultimate responsibility for diagnosis and treatment—however great the particular skills of the audiologist may be. But you may also rest assured that in all our forthcoming teaching of medical audiology to non-medical graduates, which we will be starting at Southampton University in 1972, we shall seek to make abundantly clear both the scope and the limitations of responsibility in the audiological practice to be expected of scientific and technical officers in the forthcoming Hospital Scientific Service. Then, I hope, there will be no misunderstanding as to audiology's principal role in the health service being in support of the otologist and not in any way replacing him. If we can achieve this as well as give a good training, then I think both you and your patients will obtain nothing but benefit from the introduction of higher grades of audiologist into the health and social security services.

We have some experience of this already. In the last five years there has been in the Wessex hospital region what amounts to a Regional Audiology Centre and indeed the clinical audiology section of the Institute of Sound and Vibration Research, at the University of Southampton, was on 1 March officially recognized and partially-funded as such. However, until recently about 40 per cent of the patients have been referred by just one of the fifteen otologists in the region. The point I am making is this: if a modern and comprehensive service can be so helpful to one otologist, and in the vast majority of his referrals I believe we have been helpful, then audiological investigation (which term is taken to include vestibulometric and certain 'neurometric' procedures, the rationale of which inclusion will be explained later) must surely have an, as yet largely, unrealized potential in relation to otology and neuro-otology in general.

Roles of comprehensive audiological investigation in support of the otologist

In answering the question posed by the title of this lecture, I will refer to my own clinical practice which, although related to research, amounts essentially to providing a regional diagnostic service. It may be helpful therefore to commence with a brief description of the department and of the activities conducted in it. This will be followed by a classification of the main diagnostic roles of audiology as I see them, together with some general remarks on the staffing and distribution of such special centres for comprehensive audiological investigation.

The layout of our clinical audiology section is illustrated in Fig. 1. Whilst the borders between research (Medical Research Council (M.R.C.),

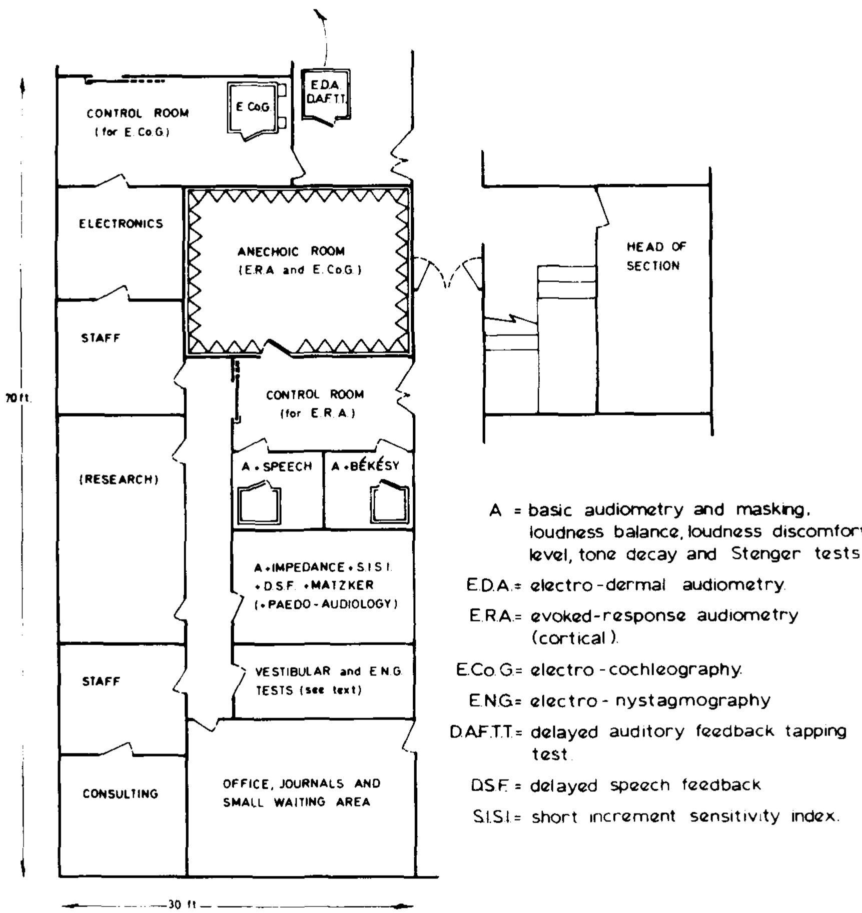

FIG. 1.

Plan and activities of clinical audiology section of the Institute of Sound and Vibration Research, University of Southampton.

Science Research Council, and Wates Foundation), teaching (Ph.D., M.Phil., M.Sc., and Cert. Med. Audiol., B.Sc.), and clinical practice are not distinct in either staff, equipment or space allocations, the plan has been restricted to show the rooms and activities directly concerned with or immediately adjacent to the clinical diagnostic work. There are of course further offices and laboratories for research work, but these are not shown in the figure nor will the additional research staff be detailed. However, it is relevant to this paper to enumerate the staff supported by the Wessex Regional Hospital Board (W.R.H.B.) in respect of our commitment to provide special audiological services for otologists in the region. The W.R.H.B. staff are the head of the section (part-W.R.H.B. and part-University Grants Committee supported), who is also an honorary consultant otologist in the Southampton University Hospitals, two part-time medical officers, a graduate audiologist, a technical assistant in audiology, a technical assistant in electronics (part-W.R.H.B., part-M.R.C.), and two part-time clerical assistants.

The principal roles in which such a comprehensive audiological service can give valuable support to the otologist are considered to be as follows:

1. Problem cases encountered in routine audiometric measurements;
2. Differential diagnosis of middle-ear disorder;
3. Distinction between sensori- and -neural hearing loss;
4. Distinction between sensori- and -neural vestibular dysfunction;
5. Electrophysiological and other forms of objective audiometry.

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6. Instrumental tests of associated cranial nerves;
7. Industrial audiology and non-organic hearing loss;
8. Tests of hearing-aid requirements.

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9. Detection of auditory disorder in C.N.S. (research stage still).

The first five items will not be discussed at this stage because they will be considered in detail later in this lecture. Moreover item 9 is as yet so little out of the research stage, in this country at any rate, that it also will not be described further, except to say that procedures such as the Matzker test appear to have considerable potential applications in support of both otological and neurological practice. Impedance tests will be discussed in some detail under item 2, but they also have a place under item 9 in that the brainstem is part of the acoustic reflex arc: they have multiple roles in fact, being involved in items 3, 5, 6, and 7 as well.

The presence of items 4 and 6 in a list of audiological investigations may raise doubts. Strictly speaking 'audio' refers to hearing, but in many disorders it would be quite wrong to limit investigation, for some administrative or semantic reason, to just the auditory part of the labyrinthine system. As suitably trained and equipped audiological staff could provide otologists with diagnostic facilities in the vestibular field also, that would not otherwise be widely or fully available, then it is only logical or include such procedures in any audiological investigation that claims or is intended to be comprehensive. Moreover, in cases of total monaural loss of hearing, vestibular tests may yield vital information as regards the likely site of lesion causing the deafness. The same argument applies to those tests of cranial nerves which are of particular interest to the otologist but which, being instrumental, are not normally available in the consulting room, and which are not obviously the responsibility of any other speciality.

Item 6. Instrumental tests of associated cranial nerves

Apart from ophthalmoscopy, instrumental techniques involving the IInd, IIIrd, IVth or VIth cranial nerves belong almost exclusively to the ophthalmological department, but there are other cranial nerve tests which can be most valuable, and which an audiologist suitably trained and equipped could usefully embrace. These are olfactometry, quantitative measurement of Vth nerve function by the threshold of corneal sensitivity, qualitative tests of the function of the VIIth nerve and its stapedial branch by means of impedance meters registering acoustic and non-acoustic stapedius reflexes and of the Vth nerve by the non-acoustic tensor tympani reflexes, quantitative measurement of the function of the VIIth nerve and its chorda tympani branch by means of the electrical taste threshold, and finally thresholds of electrical excitability of the peripheral branches of the VIIth nerve (although performance of these tests may overlap with the functions of the physical medicine department and some discussion with that department may be necessary to define spheres of activity and co-operation in tests of the facial nerve).

Item 7. Industrial audiology and non-organic hearing loss

It appears probable that, before long, noise-induced hearing loss will be included in the schedule of industrial diseases which are compensatable under the National Insurance (Industrial Injuries) Act. When this occurs there will be much additional work in the audiological and otological fields. First, the hearing losses will have to be measured carefully, under good test conditions and with accurately calibrated instruments, so as to provide a measurement of the auditory impairment on which assessment of handicap and amount of compensation payable will depend. Audiological analysis of type of dysfunction will also be needed in order to ensure as far as possible that compensation is to be paid only to those whose auditory handicap is wholly, or in major part, attributable to industrial noise exposure.

Non-organic hearing loss is likely to be a major problem here (Coles and Priede, 1971*d*). American evidence, which is supported by our own experience in investigation of medico-legal and head injury cases, suggests that some 25–40 per cent of persons claiming compensation may have a sizeable non-organic element in their apparent hearing loss. Special tests and expertise will therefore be necessary in detection of non-organic hearing loss, and having detected it, in measurement of the true organic hearing loss. Techniques for the latter include use of psycho-galvanic skin response or electro-dermal audiometry, although in my opinion this scarcely has a place now that evoked response audiometry has entered clinical practice. On the other hand, the delayed auditory feedback tapping test appears to have distinct possibilities as a measure of auditory threshold utilizing accurately quantified pure tones from an audiometer. It is therefore much more satisfactory as a quantitative measure than is the delayed speech feedback test, in which the response in most cases only occurs at some suprathreshold level (that varies between 10 and 70 dB above threshold and in some cases does not occur at all), and which is difficult to calibrate properly; this is because the test signal is the patient's own voice as he speaks, which varies in level between patients and as the test proceeds. The delayed tone feedback test is currently one of the subjects of our research. It is thought that if a clinical technique can be developed that is speedier and easier than the research one and that compares with evoked response audiometry in the reliability of the results achieved, then its relatively simple and less expensive equipment may prove preferable for use in checking the validity of conventional pure-tone measurements of noise-induced hearing loss.

Item 8. Tests of hearing-aid requirements

At the present time, audiology is probably more misused than used in regard to tests of hearing-aid requirements. Conventional speech audiometric procedures have considerable value in determining the amount of amplification needed and by indicating the potential speech discrimination ability that might be achieved if a hearing aid was used; usually this is worse with a hearing aid than with the relatively wide-frequency and high-fidelity speech audiometer, although occasionally it is better when a particular frequency-response characteristic suits the patient better and a hearing-aid providing this is utilized. The tests may also indicate the level of intolerance to amplified speech and thereby indicate both the need for some form of automatic volume control and the level at which it may be advantageous.

On the other hand, use of speech tests in a free field as a means of establishing which of a range of hearing aids is the best one for a particular ear has grave limitations. This is because for any one ear the differences in effective performance between hearing aids are quite small, assuming that comparisons are being made between aids that are not obviously ill-suited to the degree, type and characteristics of the hearing loss, whilst the confidence limits that can be placed on one speech discrimination test score are quite large; indeed, even if a full 100-phoneme phonetically-balanced monosyllabic word list is administered and the patient is carefully instructed to repeat any sounds heard (including parts of words), for there to be a 95 per cent probability that the performance of one aid is superior to another the discrimination scores may well have to differ by over 14 per cent. Of course, if a whole series of word lists are given to plot out the complete speech articulation function for each aid in turn, then speech audiometry becomes more reliable. But such procedures become far too time-consuming for general, and indeed most specialized, audiological practice. In addition, there are the variabilities imposed by the fact that a patient takes a little time to learn to respond properly to such tests and after a little time he begins to tire or lose concentration, and also by the fact that there are differences in intelligibility between word lists (which can only be corrected if the correction factors are known and appropriate to the test conditions). Moreover, there is the point that a particular aid which is best for hearing speech in one condition, e.g. in a quiet non-reverberant condition, may not be the best in a background of noise and/or in more reverberant surroundings. Finally, the use of speech tests is only appropriate quantitatively to those patients who have enough knowledge of the language for them to be able to recognize and repeat the words (in the manner that would be expected if they had in fact been heard normally).

An area where audiology may be able to help concerns attempts to restore the advantages of binaural hearing by means of hearing aids. This is another subject of audiological research at Southampton and it is hoped that it will lead, at least, to a set of rules as to when fitting of a second aid may be expected to be beneficial in cases of bilateral hearing loss or when an aid may usefully be fitted to the single deaf ear of people with unilateral hearing loss; possibly, the research may lead also to some clinical test techniques applicable in older children and adults to support the expectations derived from these rules.

Requirements for effectiveness

The full scope of investigation that has been indicated as potentially of great value to the otologist's diagnosis is clearly beyond that available or likely to become available within the present general structure of otological and audiological services. There is neither the equipment, suitable space nor sufficient time in the usual hospital clinic for the practice of more than a few of the special procedures involved. Moreover, the otologist does not (as yet, anyway) receive the special audiological training that would be necessary initially, estimated at a minimum of three months full-time, or have much spare time in which to add the constant practice and widespread further reading that would be necessary to keep him up to date with the development and interpretation of audiological techniques. The answer is not simply to increase the number of audiology technicians either, as for many modern audiological tasks the academic level needed is several grades higher than that generally found, or indeed expected, of these technicians.

The solution must surely be in the Zuckerman Committee's concept of a hospital scientific service which includes persons of scientific officer or technical officer level, in addition to those of technical assistant and technical aide which presumably embrace the present grades of audiology technician. That committee also spoke of regional centres in which specialized staff and equipment would be concentrated and give a regional service. Such centres would certainly seem to be both feasible and desirable to judge by our experience in Wessex, though in general it would be more practical and economic for them to be sited in or close to a hospital rather than in University buildings detached from the hospital. More than one such centre may be needed in large or populous regions; teaching hospitals likewise present special requirements that outside London might well be linked with the region's needs and inside London might best be organized to serve two or three teaching hospitals. Ultimately it seems likely that each hospital group or district will need to have its own audiological services up to, at least, technical officer level.

Finally, on the social security side of the Department of Health and Social Security, there will before long be a need for industrial audiology centres for the measurement and investigation of compensation claims for noise-induced hearing loss. One can only hope that in this instance the Department will act as a coherent whole so that the collection of special staff, equipment and test facilities, needed for the audiological 'centres' in both health and social security, may be combined and thereby put to maximum advantage and mutual support.

Problem cases encountered in routine audiometric measurements

Although the title of this lecture contained the words 'present day audiology' in order to signify the most modern state of the art, this should not be taken to mean that comprehensive investigation is concerned with the newer tests only, i.e. those that go beyond the basic procedures of air- and bone-conduction audiometry and masking. Indeed, some of the most important work we do in the Wessex Audiology Centre is in helping to sort out the quite frequent cases in whom particular difficulties have been encountered in routine audiometry. On occasions we have spent up to two hours on careful performance of these basic procedures alone, leaving relatively little to be gained by further investigation with the more recent techniques.

It cannot be stressed too strongly how important it is to make proper and full use of the facilities available for masking of the non-test ear in order to arrive at the real thresholds of hearing, before going on to any of the more advanced tests; only then can the correct selection and interpretation of further tests be made. The difficulty is that the less skilful or knowledgeable the audiology technician, the less is their realization of the limitations on the conclusions that can be drawn from whatever basic audiometric procedures have been carried out; the same difficulty applies to the otologist, who often has had no training in audiology or time to study it in depth, but is responsible for the professional skills and advancement of his technicians. If the basic test procedures are properly understood and performed the difficulties in given cases will be recognized, but time factors and perhaps inexperience also will probably prevent more careful measurement at the E.N.T. clinic. Reference to a specialized centre can often help, however, as will be illustrated by the following case.

The patient, one of bilateral otosclerosis, had had a successful wire-and-fat stapedectomy on the right side eight years previously, but in the eighth post-operative year had experienced over a period of about one month a deterioration of hearing in the operated ear. There were no other symptoms or signs, other than return of the unmasked air-conduction (a/c) thresholds in the right ear to their 55–65 dB pre-operative level, which were similar to those of long standing in the left ear; the Weber test at 512 Hz remained referred to the left ear and the unmasked bone-conduction (b/c) threshold levels were around 0 dB. As so often is the case with bilateral hearing loss, of conductive type in at least one ear, the b/c masking tests had been equivocal—tending to show severe b/c loss in both ears, whilst the unmasked thresholds were around normal. Doubt therefore remained as to whether the new hearing loss in the right ear was conductive or sensori-neural in type, a distinction essential to the prognosis and to any decision on possible surgical exploration of the middle ear; moreover, if the deterioration was sensori-neural in type, it would be a wise precaution to ascertain as far as possible that the lesion was sensory and not of the pathologically more important neural type.

Figure 2 illustrates, at 500 Hz only for the sake of clarity, the audiogram and the results of masking the a/c threshold determinations. That masking was needed in the a/c tests would not be appreciated if judged solely by the usual criterion, which looks for a difference of 40 dB or more between the unmasked a/c thresholds. However, this criterion is not sufficient, as discussed recently at some length by Coles and Priede (1970), and the fact that the unmasked a/c threshold levels were 40 dB or more greater than the unmasked b/c ones showed that really there was a need for masking in the a/c tests.

In virtually all the cases we investigate, but particularly those presenting difficult problems of masking, the graphs of the sort depicted are used to plot and study the masking functions for each frequency, ear and route tested. Each X or O on the masking function charts represents the threshold measured whilst a particular dial level of narrow-band masking noise was delivered by earphone (in the case of most a/c tests) to the non-test ear. Symbol Ⓜ indicates the level of masking noise that was just audible to the patient when delivered to the non-test ear. The two diagrammatic heads illustrate the particular test condition appropriate to the chart beneath it.

Taking first the left-hand chart, the threshold is seen to rise on a one-for-one basis with each increase in masking level. In passing, this illustrates well the all-too-frequent futility of masking at only one level when, as in this case, the resulting threshold determination may depend on nothing more than the level of masking delivered. On the other hand, the immediate interpretation of the whole masking function might well

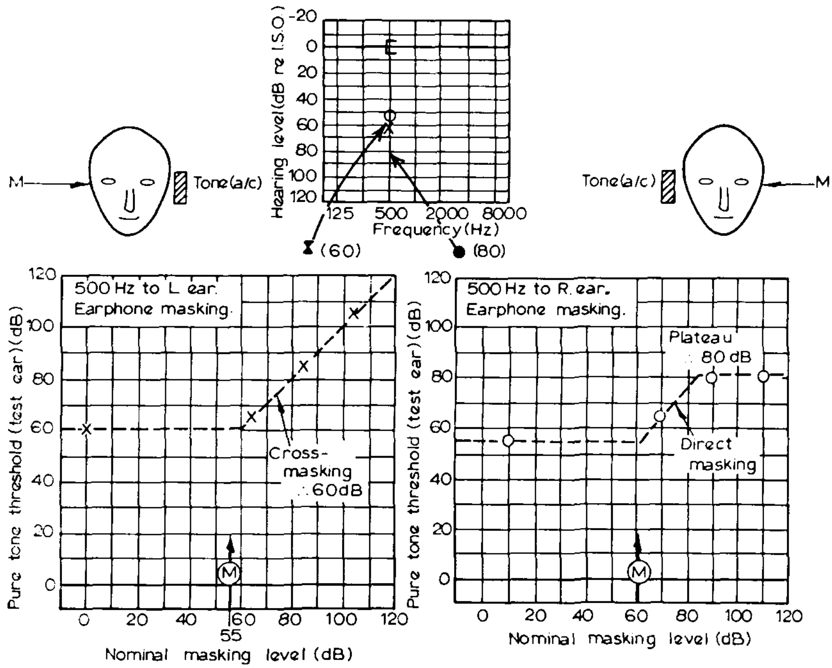

FIG. 2.

Masking of air-conduction threshold measurements, following late deterioration of a previously successful right stapedectomy.
X and O = unmasked thresholds. ⧗ and ● = masked thresholds.

be that tones delivered to the left ear were in fact being cross-heard by the right cochlea and that the masking noise delivered to the right ear was simply preventing the tones being heard by the right cochlea. This interpretation is quite possible, but it is not the only possibility. Just as the tone from an earphone can be conducted with a 40–80 dB transcranial transmission loss to the non-test ear, so the masking noise from an earphone can be conducted with a similar magnitude of transmission loss to the test ear and cause cross-masking of that ear. Now, as the right ear was deaf enough for the dial level of masking to have to be raised to 55 dB before the noise was audible, the noise level was probably high enough to have cross-masked the left cochlea, if the hearing loss in the left ear was wholly conductive, as it might well be in the particular circumstances of this case. Thus, the masking function chart obtained could equally well have been due to direct hearing and cross-masking as to the more obvious interpretation of cross-hearing and direct masking.

The right-hand masking function provided the answer, however. At first the masking noise caused a similar rise in apparent threshold, but beyond a masking dial level of 85 dB there was no further rise. This combination of initial rise followed by a plateau can be interpreted as meaning that tonal levels of 55–75 dB were being cross-heard by the left cochlea, but at and above 80 dB they were heard directly by the right cochlea; moreover, it means that there must have been a substantial element of sensori-neural loss in the right ear, which would have greatly reduced the chance of cross-masking of that cochlea.

Thus deliberate use of cross-masking and cross-hearing phenomena, together with plotting of masking functions at the same frequency for both ears and subsequent study of both functions, allowed measurement of the true thresholds with the maximum possible degree of certainty. Of course all cases are not so clear as this one, but the technique does afford the best possible estimation to be made of the true state of affairs and, perhaps more important, an indication is also available to all concerned as to the degree of confidence that can be attached to that estimation.

Similar masking functions were plotted for the b/c tests on each side, although again they were only strictly necessary for measurement of the right cochlear function. Their results indicated b/c thresholds of 0 dB in the left ear and over 50 dB in the right. The detailed masking functions will not be shown for the b/c thresholds, but it is, however, appropriate at this point to mention another technique for sorting out difficult masking problems; this involves plotting each masking function twice, once when the noise is delivered by earphone and once when delivered by insert telephone. The point is that the amount of transcranial transmission loss depends on the means by which the sound is delivered to the ear, the principal factors governing this being the area, pressure of contact and volume of air enclosed between the telephone receiver and the ear to which it is applied. Thus, compared with an ordinary earphone, greater intensities of sound can be delivered by a hearing-aid or insert type of receiver, coupled to the ear by a small plastic nipple placed in the meatus, before it sets the head into sufficient amplitude of vibration for the opposite cochlea to be stimulated, i.e. by bone conduction. Figures vary for the extent of the increased transmission loss; 15 dB is a commonly quoted figure, but an initial analysis of our own data (to be published when complete) suggests average figures of about 30 dB at low frequencies and 10 dB at higher frequencies, with individual values of -5 to $+50$ dB.

Now if the masking noise is exerting its masking effect directly on the non-test ear, that is the test tone was being heard by cross-hearing, then in most cases there will be no difference in level at which masking commences (allowing for possible average differences in calibration between the two methods of delivering the noise and for variations in sound field due to variations in the exact placement of the insert in the ear canal). If the effect of the masking noise delivered to the non-test ear is in fact exerted on the test ear, that is by cross-masking, then the level at which cross-masking commences will be from -5 to $+50$ dB higher in the case of the insert telephone. Comparison of the masking functions of the two sides is again helpful here, and we have come to regard differences between insert and earphone masking that are 20 dB greater on one side than the other as highly suggestive of cross-masking on the side which exhibits the greater difference.

Such tests are complicated and time-consuming, but this is surely a useful function of more meticulous audiological investigation in selected patients. But before going on to my next subject, I would like to complete the story of this particular patient.

There had been a fairly rapid but not a sudden deterioration of hearing in the right ear and the audiometry showed its hearing loss to be predominantly if not entirely sensori-neural in type. A dislocation of the prosthesis, leading to the equivalent of an ossicular discontinuity, could not therefore be the diagnosis. Impedance tests, notably those with the Zwislocki acoustic bridge in this case, showed a compliance that was greater than is usual with post-stapedectomy patients yet, as expected, less than usual with a complete discontinuity. What could have happened? We postulated, but have not had the opportunity of surgical confirmation, that the wire prosthesis had dislocated medially; that is, through the post-operative membrane over the oval window. This would then still transmit acoustic signals and thereby account for the lack of any large amount of conductive deafness, but it would reduce the stiffness of the ossicular chain and thereby account for the increased compliance. It would also account for the sensori-neural hearing loss either by direct damage to the membraneous labyrinth or by causing a perilymph leak.

Finally, tests of tone decay and of discrimination ability were performed; fixed-frequency Békésy audiometry and S.I.S.I. tests were selected because of the levels of masking needed could be read off the a/c masking function charts already obtained. These confirmed, as far as they could, the cochlear site of the lesion causing the sensori-neural hearing loss.

Differential diagnosis of middle-ear disorder

An example of the potential value of absolute measurements of acoustic impedance has already been given in the section above. However, in our experience, the Madsen type of electro-acoustic impedance meter which is now to be found in many otological clinics in this country is generally a much more versatile instrument. Recent versions of it can give absolute measurements of compliance at one frequency, 220 Hz., but in general its ready ability to give quantitative indication of *changes*

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of impedance, or 'relative' impedance, is its great virtue. There are three ways of inducing changes of impedance.

First, an acoustic stimulus in the contralateral ear, i.e. the one opposite to the ear containing the impedance probe, may induce an acoustic reflex, whose threshold may be measured in terms of a pure tone of known hearing level. This has many applications; as a measure of recruitment (to be discussed), as an objective though suprathreshold measurement of hearing ability (impedance audiometry) of use in children and also sometimes in cases of non-organic hearing loss, as a test of integrity of brainstem function which mediates the central part of the acoustic reflex arc, as a test of integrity of the VIIth nerve and its stapedial branch, and as a test of normality of movement of the ossicular chain and tympanic membrane in response to stapedius muscle contraction (stapedial reflexes can rarely be detected by means of impedance tests where there is conductive deafness in excess of 15 dB in the ear with the impedence probe in it).

Second, non-acoustic reflex stimulation of middle-ear muscle activity can help to differentiate the possible cause of an absent acoustic reflex. This can be done by an ipsilateral orbital air puff which produces a tensor tympani response, or by a contralateral aural air puff which produces a combined acoustic and non-acoustic stapedius response. Other non-acoustic stimuli have been described and tried, but we find the above two the easiest to perform and the most useful clinically.

Third, there is the procedure known as tympanometry, which is probably the most useful single facility provided by relative impedance meters. A positive air pressure, of +200 mm water pressure relative to the atmospheric pressure, is introduced through the impedance probe in the external meatus. This sets up a pressure differential across the tympanic membrane which stretches it medially and restricts its vibration in response to the 220 Hz. probe tone also delivered by the impedance probe. Whilst the tympanic membrane and associated structures are thus at maximum impedance, the instrument is 'balanced' electro-acoustically to give a minimum deflection on its indicator meter. The pressure in the external meatus is then gradually lowered. As the tympanic membrane is gradually relieved of the stretching force, it becomes more free to vibrate and its acoustic impedance returns towards normal, i.e. lower, values; the previously adjusted electro-acoustic balance is then increasingly upset, as indicated by an increasing deflection of the meter needle. The pressure change is continued until a negative pressure of up to −400 or −500 mm. water pressure is reached. With negative pressures, the tympanic membrane becomes stretched laterally, and gradually becomes less free to vibrate again; the acoustic impedance then rises again, and the meter needle returns towards its original 'balanced' condition of minimum deflection. The point at which the tympanic membrane has no pressure differential across it corresponds of course to its condition of maximum freedom to vibrate in response to the probe tone. Thus, the acoustic impedance will be at a minimum and the meter deflection at a maximum when the external meatal pressure equals that in the middle ear; as the former is indicated by the manometer on the impedance meter, a measure of the middle-ear pressure is obtained.

The great clinical diagnostic value of such a measurement is obvious, although some may say that there is no need to measure the middle-ear pressure because it can be judged from the otoscopic appearance of the tympanic membrane and its response to pressure changes using the Siegle speculum. Certainly it can be so judged, but how reliably? All I can say is that if you make a practice of measuring the middle-ear pressure and the compliance you will be surprised how frequently they have been misjudged. Retraction and reduced mobility do not necessarily mean a reduced middle-ear pressure, whilst quite low middle-ear pressures are not always accompanied by obvious retraction and reduced mobility.

Reductions of middle-ear pressure cause, *per se*, relatively little hearing loss, as measured recently in our laboratory (see Table 1 below). They do, however, indicate a dysfunction of the Eustachian tube that may be accompanied or followed by such other pathological features as effusion or fibrosis, which in turn will increase the hearing loss. Thus,

TABLE I.

EFFECTS OF EXTERNAL/MIDDLE EAR PRESSURE DIFFERENTIALS UPON HEARING.
(N = 10 otologically normal subjects)

Pressure differentials (mm water)	Mean (and range) of the shifts (dB) from the thresholds at zero pressure differential, at selected test frequencies (Hz)					
	250	500	1,000	2,000	4,000	8,000
25	0·5 (−5 to 5)	2·5 (−5 to 10)	2·5 (0 to 10)	0·5 (−5 to 5)	0·5 (0 to 5)	1·5 (0 to 5)
50	0·5 (−5 to 5)	3·0 (0 to 5)	2·0 (−5 to 10)	1·5 (0 to 5)	1·0 (0 to 5)	2·5 (0 to 5)
100	2·5 (0 to 5)	5·0 (0 to 10)	3·0 (0 to 10)	2·0 (−5 to 10)	0 (−5 to 5)	3·5 (0 to 5)
200	5·5 (0 to 10)	8·0 (0 to 15)	6·5 (0 to 15)	3·0 (0 to 15)	1·0 (−5 to 5)	4·0 (0 to 10)
300	7·0 (0 to 15)	10·0 (5 to 15)	10·0 (5 to 15)	5·0 (0 to 15)	3·5 (−5 to 10)	4·5 (0 to 15)
400	10·5 (5 to 15)	15·0 (10 to 25)	12·5 (10 to 15)	6·5 (0 to 15)	4·0 (−5 to 15)	5·0 (0 to 15)
500	11·0 (5 to 20)	15·5 (10 to 25)	14·0 (10 to 20)	8·0 (0 to 20)	6·0 (0 to 15)	7·0 (0 to 20)

The pressure differentials are all in the direction of a higher pressure in the external than in the middle ear. Negative threshold shifts indicate an apparent improvement in hearing.

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knowledge of the middle-ear pressure permits estimation of how much of the hearing loss can be attributed purely to the low pressure, and may therefore be immediately correctable, and how much may be due to secondary or associated pathology (although relief of the pressure differential could alter the distribution of an effusion and thereby occasionally cause greater immediate improvement than to be expected from the figures shown in Table I).

Further, middle-ear pressure measurement has other uses. It permits the acoustic and non-acoustic reflex tests to be done at an external meatus pressure equalized to the middle ear pressure, which allows maximum sensitivity to reflex tests. It also enables accurate measurements of absolute impedance to be made (at 220 Hz. at least) that are independent of middle-ear pressure effects, even when there is lowered middle-ear pressure, and helps the interpretation to be put on other absolute impedance measurements obtained for instance with the Zwislocki bridge. Lastly, it provides another method of demonstrating a positive Valsalva or Toynbee manœuvre in those not-infrequent cases where the tympanic membrane movement is very difficult to see otoscopically.

The value of tympanometry goes further. The amount or rate of change of impedance gives a measure of the acoustic impedance in the plane of the tympanic membrane. Although this is not yet satisfactorily calibrated with some, e.g. Madsen, commercial instruments, it can nevertheless provide useful semi-quantitative data and in the near future the calibration deficiency is likely to be resolved. Despite the fact that there is a fairly wide normal range of impedance, in which unfortunately most of the otosclerotics seem to lie as found in other forms of absolute impedance measurement (Bicknell and Morgan, 1968), deviations from this range have diagnostic value. A rapidly-changing impedance may be found not only in a thinly scarred or generally hypotrophic tympanic membrane (not always detected initially due to uncertainty of airtight fit of aural specula), but also in those cases of ossicular discontinuity where there is no post-traumatic or post-infective fibrotic restriction on movement of membrane, malleus and/or incus. Changes of impedance below the normal range occur in some cases of otosclerosis, in tympanosclerosis, with an obscure perforation (or patency of a grommet) and in middle-ear effusion. The combination of reduced middle-ear pressure with little change in impedance as the external meatus pressure is altered can provide valuable evidence additional to the clinical signs as to the state of the middle ear in cases of secretory otitis media (Brooks, 1968).

Distinction between sensori- and -neural hearing loss

The recruitment group of tests

The use of the acoustic reflex threshold (A.R.T.) as a test of recruitment has already been mentioned. In this respect it can be compared with the loudness discomfort level (L.D.L.) test, first put on a properly quantitative basis by Hood and Poole in 1966, except that the A.R.T. occurs at about 15 dB lower intensity levels in normal persons and is an objective test as compared with the highly subjective L.D.L. Unfortunately it suffers from the same disadvantage: namely, it rarely does more than indicate presence of some, uncertain, degree of recruitment.

There is a widespread misconception regarding the significance of presence of recruitment; indeed, of itself, simple presence of recruitment is not a very helpful differential diagnostic finding. The trouble is that a considerable proportion of cases primarily with retrocochlear site of lesion exhibit some degree of recruitment. This is not only our own finding; indeed, it only lends further support to the earlier observations of Dix and Hallpike (1958) and Johnson (1965), the former finding *complete* (let alone partial) recruitment at one or more frequencies in some 10 per cent of acoustic neuromata.

By and large, one can say that there is a strong possibility that an auditory disorder is sensory in type, i.e. of the hair cells (often, incorrectly, regarded as synonymous with end-organ or cochlear, see the definition of terms given in the next section), if recruitment is complete or if there is over-recruitment. On the other hand, our data, like those of Jerger (1961), Lidén (1970) and others, have failed to show the almost invariable presence of complete recruitment in Ménière's disease (in 415 out of 424 cases) reported by Hood in 1969. It appears that differences in test methodology account for some of the discrepancies between various published series of cases, but our experience at Southampton using both the principal methodologies, sometimes for research purposes in the same patient, leads us to believe that incomplete recruitment occurs rather frequently in the more heterogeneous collection of 'cochlear' cases that is found in the normal run of otological practice. Thus, whilst complete recruitment means probability but not certainty of a purely sensory lesion, lack of complete recruitment, even using Jerger's (1962) 10 dB less exacting definition* than Hood's, does not necessarily mean that the lesion is primarily neural in site; that is, incompleteness of recruitment may arise from an element of neural degeneration that is secondary to a hair-cell lesion or, in severe sensory damage, from there being too few high-intensity sensors left for normal growth of sensation of loudness even at the highest intensity levels.

At the other end of the scale, however, a more definite rule can be made. If there is absence of recruitment, then the primary lesion is almost certainly of neural site; and the presence of actual loudness reversal can be taken as pathognomonic of a neural lesion.

*Jerger's definition of complete recruitment requires the equal loudness line to come only as close as 10 dB from the equal intensity line (as visualized in the sort of graph shown in Fig. 3.)

Between these two extremes, of complete and absent recruitment, there is of course a continuum in degree of recruitment. There is also a continuum in relative probability of a primarily cochlear or retrocochlear site of lesion, and in general it is fair to interpret the results by this means; that is, the nearer completeness of recruitment, the greater the chance of the lesion being primarily cochlear in site. It is necessary though to reserve a high degree of suspicion regarding *any* instances of partial recruitment, and one must be aware of the limitations of many recruitment tests with respect to proof of completeness of recruitment.

Thus it is not sufficient just to know that there is recruitment present, but we need to know how much recruitment is present. Unfortunately, the normal range of A.R.T. and L.D.L. measurements is so wide, 70 to over 120 dB H.L. in the case of A.R.T. and 75 to over 120 dB H.L. in L.D.L., that in most instances lack of recruitment cannot be inferred from such measurements in just one ear, or in both ears if both are impaired; if one ear is normal, comparison of the A.R.T. or L.D.L. values in both ears is more informative in that they can be used as a single-level form of loudness balance, but in those circumstances the most informative, multiple-level, alternate binaural loudness balance (A.B.L.B.) test of Fowler should be applied.

Sometimes, if the hearing threshold is high enough and the A.R.T. and/or L.D.L. low enough, the presence of complete recruitment can be deduced. Using the 95 per cent limits of confidence (twice the standard deviation) shown in the A.B.L.B. recruitment functions of cases with Ménière's disease published by Hallpike and Hood in 1959, and applying the normal lower limits of A.R.T. and L.D.L. values found in our own studies, together with A.R.T. and L.D.L. data from patients with known causes of sensori-neural hearing loss, Priede (1971) has recently derived some interim criteria for use in our own work by which individual values of A.R.T. and L.D.L. can be interpreted for clinical purposes. Whilst she may well adjust these slightly when more comprehensive analyses of recruitment functions currently being carried out are completed, they are useful in their present form and are therefore reproduced here. Table II relates A.R.T. and L.D.L. values to threshold hearing levels (H.L.) in terms of likelihood of complete recruitment, i.e. of there being a predominantly sensory type of disorder of function.

It can be seen at once that these criteria are somewhat stringent and the majority of cases, even of purely sensory dysfunction, are unlikely to meet them. Therefore in order to ascertain the amount of recruitment, the A.B.L.B. test (whenever applicable) should be used. For this reason, as well as for the more complete information on the loudness function that it affords, the A.B.L.B. test remains the most important of recruitment tests. But it too has its failings, not only, as already discussed, in its diagnostic value but also in its reliability. First, it is not always sufficient to perform a range of loudness balances at just one frequency: we have had cases of acoustic neuroma where incomplete recruitment has occurred only at high frequencies, although in one case the hearing loss also was only at 6000 and 8000 Hz. Second, some patients find the psycho-acoustic task of loudness balancing difficult and one questions their reliability.

An example of both problems is shown in Fig. 3. Here, in Mrs. N. P., a case suspected of having a small right acoustic neuroma, there was complete recruitment at 1000 Hz. but incomplete recruitment at

TABLE II.

CRITERIA FOR ASSESSMENT FROM A.R.T. AND L.D.L. DATA OF LIKELIHOOD OF COMPLETE RECRUITMENT OR OF PRESENCE OF A PREDOMINANTLY SENSORY TYPE OF DISORDER OF FUNCTION (AFTER PRIEDE 1971).

(All values in dB re normal threshold of hearing)

Threshold* hearing level (H.L.)	Acoustic threshold reflex (A.R.T.)	Loudness discomfort level (L.D.L.)
20 or more	80 or less	85 or less
40 or more	85 or less	90 or less
60 or more	90 or less	95 or less
80 or more	95 or less	100 or less

Any A.R.T. or L.D.L. value that is within 16 dB of the H.L.

* This refers to the true (masked) threshold.

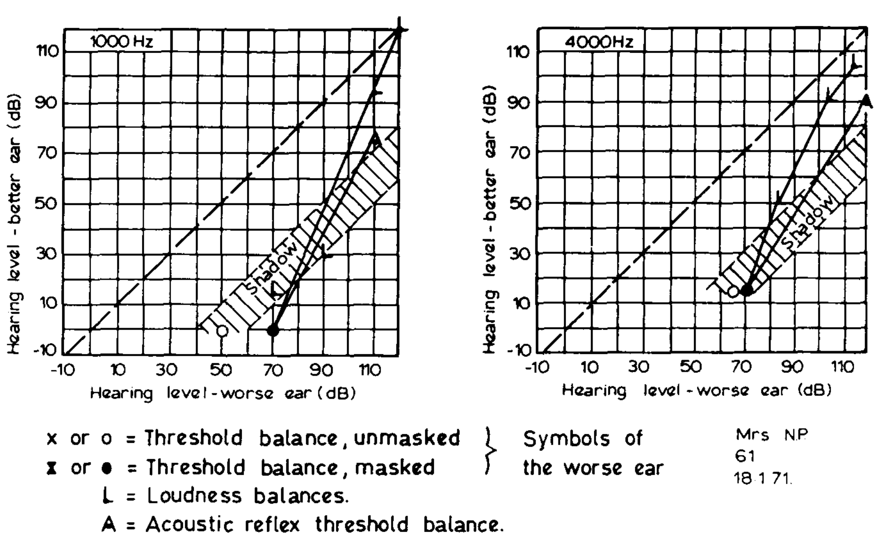

FIG. 3.

Alternate binaural loudness balance (A.B.L.B.) test results.

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4000 Hz., as judged by Hood's definition though falling within the 10 dB. tolerance allowed by Jerger. But the A.R.T. measurements performed allowed the A.R.T. balances to be plotted also and these showed much less than complete recruitment; one is left with the feeling that the objective A.R.T. balances may well have been a more accurate expression of the true loudness functions than the subjective A.B.L.B. ones, especially when one takes into account the high probability from other tests that there was a neural lesion. A case can be made for the desirability of utilizing both A.R.T. and A.B.L.B. tests of recruitment wherever possible.

In passing, there is another feature in Fig. 3 worthy of comment. It is helpful in interpretation of A.B.L.B. data to consider both the unmasked and masked thresholds of the worse ear and to plot both forms of threshold balance on the loudness function chart. Although the A.B.L.B. is performed without use of masking and the first loudness balances may simply be a shadow ($\pm$10 dB) of the better ear, as in the 1000 Hz. test shown, the real loudness function line should of course originate from the true (masked) threshold of the worse ear. This is yet another example of the need for precise and accurate use of masking in the basic audiometry before differential diagnostic tests are applied. Another example would be where there was an element of conductive deafness, for example 10 or 20 dB in the worse ear; this would have to be allowed for in assessment of the degree of recruitment in the sensori-neural element of the deafness.

Other tests in sensori-neural hearing loss

At this point I'm sure you will be wondering what can be done to distinguish cochlear from retrocochlear lesions if recruitment tests have so many limitations. This is where all the other tests come into play: not as alternatives to the recruitment of tests, but as additional help towards correct identification of site of auditory dysfunction. The additional tests fall into two groups, tests of abnormal adaptation and tests of abnormal auditory discrimination.

If time, skill, apparatus and the patient's ability to respond accurately were unlimited, one could say 'the more tests, the better the diagnosis'. Obviously there are limits though, and a compromise that can still be regarded as a comprehensive investigation is, in the case of sensori-neural hearing loss, to perform one test each from the second and third groups named above, in addition to one test in the recruitment group, preferably the A.B.L.B. test.

But before going on to illustrate the second and third groups of tests, one vital proviso must be stated. Unlike recruitment tests, masking of the non-test ear is nearly always necessary with any of the tests in the other two groups—even with the S.I.S.I. test. If masking of basic audiometry is often poorly understood and performed and is sometimes very complicated, masking of adaptation and discrimination tests is even less well understood and more difficult. It is barely covered in textbooks or in the literature, although it is apparent that there is a very real demand for information on the subject and this has led to two papers that are currently in the press (Liden, 1971, and Coles and Priede, 1972*b*). Further description cannot be given here but I have taken the liberty of indicating, in the next two figures, the diametrically opposite result that would have been obtained had masking not been used.

The abnormal adaptation group of tests

The two most common tests in this group are (i) the threshold tone decay test, described first by Carhart and subsequently with variations by other authors and (ii) Békésy audiometry according to the method advocated by Jerger (1962). In the latter, comparisons are made between the threshold tracings recorded first with interrupted tones, when no tone decay occurs, and then with continuous tones when adaptation can occur. The degree of separation of the two traces is a measure of the degree of tone decay and various patterns have been described by Jerger (types I to IV) and by others. Of the two tests, we prefer Békésy audiometry on the grounds that, in its sweep-frequency form, it scans through the whole frequency range and seems to yield fewer false results. When it is appropriate to take a close look at a particular frequency, or when there are difficulties in masking, we use the fixed frequency form of Békésy audiometry though; and when the patient finds the self-recording task too difficult, or a quick check on lack of tone decay is needed, or limitations imposed by the hearing level being close to the maximum output of the audiometer, we employ the Owens' technique of tone decay test. The results of sweep-frequency Békésy audiometry in Mrs. N. P. are shown in Fig. 4.

The pattern shown by this patient does not fall precisely into the type III or IV classification of Jerger, but quite certainly demonstrates a degree of adaptation that is considerably greater over much of the frequency range than the maximum of 20 dB that may occur in a predominantly sensory type of dysfunction.

But note that if masking had not been used, the continuous tones delivered to the right ear would have been heard by the non-test ear before they reached the decayed threshold level of the test ear; and, as the non-test ear was not pathological and therefore little or no tone decay would occur in that ear, the tracings of continuous and interrupted tones would then have overlapped and a type I pattern have resulted. Thus, without masking there would have been no suggestion of the all-important neural type of dysfunction; with masking (which has to be increased in level as tone decay is recorded) there was strong evidence for the neural type.

The abnormal auditory discrimination group of tests

The two main tests here are speech audiometry and the short increment sensitivity index (S.I.S.I.). Of these, we much prefer the former, as it gives a highly reliable indication of site of lesion; moreover, it is a test which the patient understands, it has other diagnostic value in relation to the ever-present possibility of presence of non-organic hearing loss,

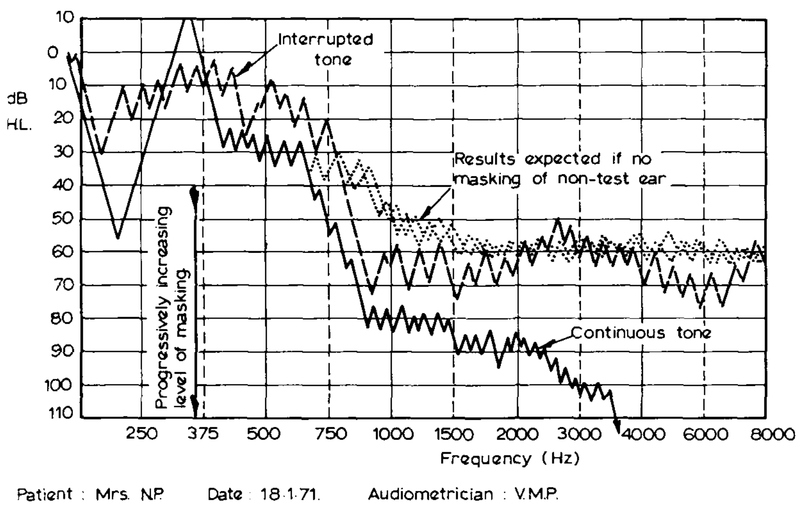

FIG. 4.

Békésy audiogram showing type III/IV pattern of tone decay.

and it gives information on the patient's most important auditory function —that of his hearing ability for speech. Occasionally however the S.I.S.I., in a modified high-presentation-level form, has been the discrimination test of choice; for example, if a test at a particular frequency is required, if the speech tests are limited by the upper intensity limit of the speech audiometer or of the wide-hand noise masking available, or if there is special difficulty in masking. The details of this test, our modification of it, and the reason for regarding it as a discrimination test rather than a recruitment test, are all beyond the scope of this lecture but will be published in due course.

The speech audiogram of Mrs. N. P., shown in Fig. 5, illustrates the gross abnormality of speech articulation function that is usually found in an ear (her right one) with a neural type of disorder. Also indicated is the area in which the speech articulation curve could have been expected if it had been of sensory type, and the expected results of testing the right ear if the non-test (left) ear had not been masked—when the apparent right ear results would merely have been a shadow of the left ear. It can be seen therefore that without masking a result compatible with a sensory dysfunction could easily have resulted, whilst only with masking was the true state of affairs revealed.

The reliability of speech audiometry, suitably masked, as an indicator of a neural disorder is high but depends on (i) proper use of masking, and (ii) knowledge of the discrimination scores to be expected from given degrees of sensory hearing loss, when using the particular set of word lists, speech audiometric equipment and method of intelligibility scoring. This knowledge has recently been derived from our research (Priede, 1971)

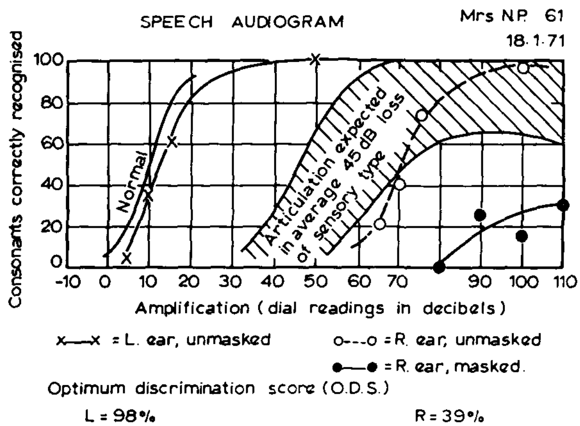

FIG. 5.

Speech audiogram showing excessive speech discrimination loss in a patient with an auditory nerve lesion.

with respect to Fry's tape-recorded phonetically-balanced word lists, played from a high-quality tape recorder (Ferrograph) through a speech audiometer attachment (Amplivox) to a conventional audiometer earphone (Telephonics TDH–39). The relationships, plotted for a series of patients with primarily cochlear or retrocochlear lesions, of acquired type, between the optimum phoneme discrimination score and the pure-tone hearing level (average of best two of the central speech frequencies, 500, 1000, 2000 Hz., plus 0–4 dB according to slope of audiogram) are illustrated in Fig. 6.

As one might expect, the discrimination scores achieved by the cochlear cases were inversely proportional to their hearing level. The same is true though to a lesser extent with the retrocochlear cases; but, more important, their scores were in the majority of the cases well below those with cochlear disorders. Although there is quite a wide spread of O.D.S. values, there is relatively little overlap between the distributions for sensory and neural cases. Indeed, the dashed line across the graph depicted in Fig. 6 provides a 'criterion' of great clinical usefulness; thus, 90–95 per cent of the cases with lesions primarily of cochlear type had speech discrimination scores above the line and a similar proportion of those with primarily retrocochlear lesions (especially the VIIIth nerve tumours) had scores below the line.

This is considerably better than the results we, and others, have achieved with the A.B.L.B. test and, moreover, the test is applicable to

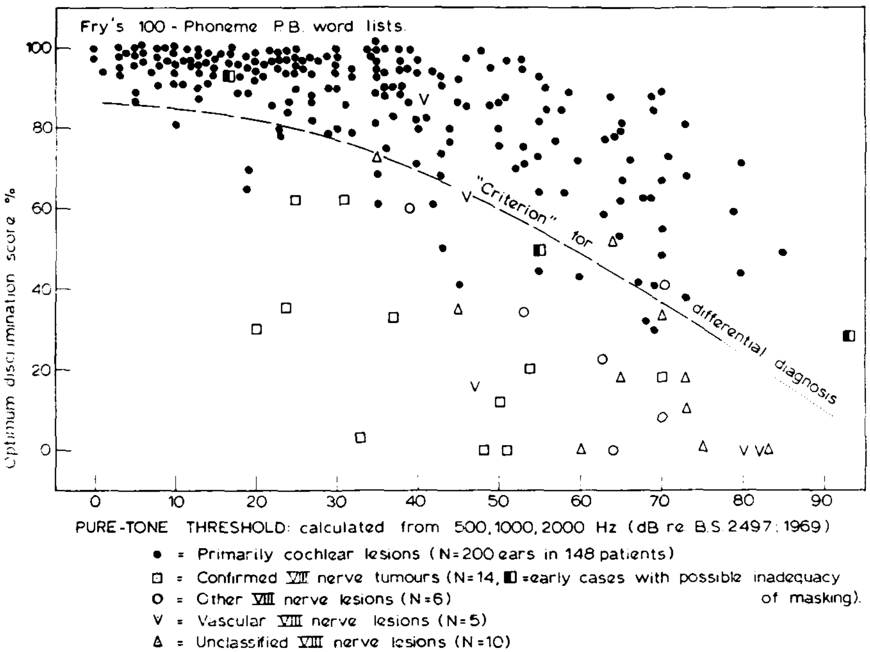

FIG. 6.

Relationship between speech discrimination score and pure-tone threshold in cases of acquired cochlear or retrocochlear lesion (after Priede, 1971).

bilateral lesions. Thus, properly masked, speech audiometry appears to be a very valuable differential diagnostic tool in sensori-neural hearing loss, in addition to its other merits. It is appropriate therefore to enlarge on its use for this purpose by mentioning some details and extensions needed. It is not satisfactory to do the discrimination test at some arbitrary level, say 50 dB above calculated or measured speech reception threshold, or at a level based on the patient's judgement of most comfortable listening level. This may not yield the optimum score, and the less than optimum score obtained may be mistaken as indicative of a neural lesion. Instead we have found it necessary to investigate the whole speech articulation function, using a series of short word lists at 10–20 dB intervals, which then allows a proper selection of the optimum level for presenting a full 35-word (100-phoneme) list. Moreover, the complete articulation function itself adds further information of diagnostic value. Cases with incipient neural lesion have been described elsewhere, and we have seen one such case too, in which there was little or no hearing loss for pure tones but there was distinct abnormality in the speech articulation function, such as a very slowly rising curve or an acceptable optimum discrimination score but with very little speech intelligibility on either side of the optimum level; had the full range of speech intensities not been investigated in such cases the neural type of dysfunction would not have been detected.

Distinction between sensori- and -neural vestibular dysfunction

Before going on to describe the various test procedures involving E.N.G. which we utilize and to outline their main diagnostic interpretations, it would be helpful to define the anatomical terms to be used. 'Sensory' refers to the hair cells of the auditory or vestibular receptors in the labyrinth and 'neural' refers to the auditory or vestibular pathways from the nerve fibrils in contact with the hair cells right up to cerebral cortex level. 'Peripheral' refers to lesions sited either in the sensor cells or in the first-order neurons, i.e. those afferent neural elements that are outside the central nervous system (except for the small intra-medullary part of the auditory and vestibular nerve fibres which synapse with the cell bodies of the second-order neurons in the cochlear and vestibular nuclei); 'central' refers to the second and higher order neurons of the system. Neural sites can therefore be subdivided into 'peripheral neural' and 'central neural'.

In general, tests of the auditory system distinguish between types of disordered function characterized by sensory or neural (either central neural or peripheral neural) patterns of response. In contrast, most of the tests of the vestibular system distinguish between peripheral (either sensory or peripheral neural) and central types of disturbance.

In describing patterns of disturbed *function*, it is best to avoid use of words such as 'cochlear', 'end-organ' or 'labyrinthine', and 'retrocochlear' or 'retrolabyrinthine', and to reserve these for description of the anatomical locus of the lesion causing the disturbance of the function. The trouble is that a lesion of the labyrinth can, by direct pathological involvement or by secondary degeneration, include not only hair cells but also neural elements such as the peripheral nerve fibrils and ganglia. Likewise a lesion of the nerve can masquerade as a lesion of the hair cells, probably by interference with their blood supply or by a chance pattern of nerve fibre damage. Thus, 'sensory' and 'labyrinthine', or 'neural' and 'retrolabyrinthine', should not be regarded as synonymous terms. For instance, an acoustic neuroma has primarily a retrolabyrinthine pathology but it sometimes causes secondary lesions of the cochlea and hair cells; likewise vascular lesions can cause mixed neural and sensory signs, presumably due to multiple sites of ischaemia in some cases.

The reason for including electro-nystagmography (E.N.G.) as part of a comprehensive investigation by audiological staff in support of the otologist has already been explained. What therefore can it offer, supplementary to the ordinary clinical techniques of vestibular investigation? The advantages are threefold: (i) it provides a more satisfactory means than by Frenzel's glasses of comparing the effect of presence or absence of visual fixation on spontaneous and/or induced nystagmus, (ii) by testing with eyes closed or, better, with eyes open in darkness, much of the normal visual-fixation inhibition of nystagmus is removed and the test consequently gains in sensitivity, and (iii) it is more easily quantified and allows measurement of the velocity of the slow phase of nystagmus, which is more directly related to the response of the vestibular system to a nystagmus-inducing stimulus or tonal imbalance than is the case with measurement of duration of nystagmus. Moreover, it is considered that a suitably trained audiologist can perform all the tests, including calorics, provided the ears are medically certified beforehand as fit for irrigation and medical advice is immediately available should any problem arise—similar qualifications to those applying to a nurse in syringing an ear for removal of wax.

Spontaneous nystagmus may be enhanced or revealed for the first time when visual fixation is removed; this is characteristic of the nystagmus produced by a fairly recent or rapid change in the resting tone of the peripheral vestibular activity, i.e. due to a disturbance of the sensory or peripheral neural part of the system. It has to be fairly recent and/or sizeable because long-term adaptation abates the signs and symptoms even from a severe vestibular imbalance; and it has to have occurred fairly rapidly, otherwise adaptation keeps pace with the development of imbalance, as in the case of the slowly increasing pressure effects of an acoustic neuroma.

On the other hand, if the spontaneous nystagmus recorded by E.N.G. is reduced in slow-phase velocity or abolished by removal of visual fixation, then the disturbance is of the central neural type, probably with an anatomical locus at or a little above the vestibular nuclei (Dix and Hallpike, 1966).

We have not found much additional benefit from using E.N.G. in performing positional nystagmus tests. Without visual fixation there is some gain in sensitivity, but small degrees of vertical, oblique or rotatory nystagmus visible by direct observation are apt to be missed in the recordings. On the other hand, we have recently started doing a neck position test; with the eyes closed, the patient turns his neck as far as possible to one side and holds it there for 20 seconds, then to the other side, then fully extended, and finally fully flexed. It is surprising and gratifying to find how often patients with somewhat vague and atypical symptoms of vertigo, sometimes even suspected of being psychogenic, may then produce a typical labyrinthine type of nystagmus. Presumably this can arise from disordered neck reflexes as from cervical spondylosis or trauma, or from a deficiency in the vertebro-basilar arterial supply of the hind-brain and/or internal ear. Another possibility is that, even if the neck and arteries are normal, these manœuvres may result in a reduction of blood supply; in normal persons this would presumably have no effect, but where there is already an abnormality of either the peripheral or the central parts of the labyrinthine systems the reduced blood supply might cause symptoms or recordable nystagmus. More work needs doing on this, but it does at least provide useful evidence that the patient's symptoms are based on some organic disorder and this is often supported further by radiological findings of abnormality in the cervical spine. It also helps to sort out those cases of positional nystagmus which are induced not so much by labyrinth orientation as by neck position.

In caloric tests, E.N.G. is a help whenever there is a spontaneous nystagmus and the end-point or duration of induced nystagmus cannot be recorded. More important though, it is a great help where conventional caloric tests, with visual fixation and direct observation of the nystagmus, have failed to reveal any response to caloric stimulation. Such a lack of response in the presence of an active vestibular system may occur under two circumstances.

Firstly, the irrigation may have been inadequate; that is, it may not have reached the deep part of the external meatus. Because of this frequently-encountered difficulty and uncertainty, rotational tests are preferred by some investigators as a more certain means of delivering a stimulus of precisely known magnitude—unfortunately to both ears simultaneously though, which drastically reduces its diagnostic usefulness. A technique which we have found extremely valuable in ensuring the adequacy of caloric irrigation is, as soon as possible after the hot (44 °C) irrigation, to inspect the tympanic membrane. In the vast majority of cases, a marked hyperaemic flush down the handle of the malleus, of the tympanic membrane, and/or of the wall of the deepest part of the bony meatus is visible immediately after an adequate irrigation, becomes maximal after 60–90 seconds from the start of irrigation and in most cases persists for five minutes or longer. This is much less obvious and slower to develop after the cold (30 °C) irrigation, though after very cold (20 °C) tests a marked flush is sometimes seen, possibly due to a reactive hyperaemia. For this, and other reasons, we always perform the hot tests first; and if, with the eyes open in darkness, no recordable nystagmus is induced and there is no visible flush in the ear, then the irrigation is repeated with the greatest possible care to ensure as far as possible that the flow of water penetrates to the depths of the meatus. In many instances a nystagmus previously absent then becomes evident; but, as a corollary, we are very guarded about an apparent absence of caloric nystagmus in the occasional instances in which he had been unable to demonstrate the adequacy of stimulus by this 'tympanic flush sign.'

Secondly, the caloric nystagmus may have been inhibited in the usual tests performed with the eyes open in the light, i.e. with visual fixation. Such strong inhibitions occur either occupationally, classically in ballet dancers (Dix and Hood, 1969) and figure skaters, but also in sailors and other persons with frequent occupational exposure to high level or prolonged vestibular stimulation, or as a result of pathological processes resulting in severe vertigo, for example, following vestibular neuronitis (Dix and Hood, 1970). Some degree of inhibition is normal and indeed an optic fixation index for caloric-induced nystagmus,

$$= \frac{\text{slow phase velocity with visual fixation}}{\text{slow phase velocity without visual fixation}},$$

that is below about 0·5 is found in normal persons and those with peripheral vestibular lesions (Ledoux and Demanez, 1970).

Most of these tests help to distinguish between central and peripheral sites of lesion but not between one peripheral site and another, i.e. between sensory and peripheral neural. For instance, our Mrs. N. P. had a right canal paresis, and this could just as well have been due to a hair-cell as a nerve lesion. However, there is one technique recently described by which information can be gained that may help in differentiation of sensory from neural types of disordered function. This is known as thermal vestibulometry (Litton and McCabe, 1967). In essence, it is an extension of the caloric test carried out in absence of visual fixation and with E.N.G. recording. Progressively stronger stimuli are given and the response to each is measured; we use water at 25°, 20° and 15 °C, and measure the maximum velocity of the slow component of the induced nystagmus. The results, together with the conventional 44° and 30 °C caloric test responses, are then graphed in the manner shown in Fig. 7.

Utilizing our own experience, in 31 such cases up to the time of writing, and the published data of Litton and McCabe, examples are shown of the various patterns of response that can result. In both normal persons and in those with sensory disorders there is a fairly linear growth of response as the strength of stimulus grows, although where there is a severe canal paresis as in example 'A' the growth rate is small. The slight deceleration of growth of response is presumably the result of adaptation or habituation, though by spacing out successive tests by intervals of not less than ten minutes habituation is minimized. The opposite, an acceleration of the growth of response, which would correspond to a form of vestibular recruitment, does not seem to occur though. The deceleration of response growth becomes marked in cases of neural site of disordered function, presumably due to the abnormal adaptation so often found of nerve lesions; this is termed 'vestibular fatigue' by Litton and McCabe. In some instances, example 'B', the curve merely flattens off, but in others ('C', 'D' and 'E') the response eventually decreases with increasing strengths of stimulus; these patterns have been found in central vestibular lesions, but, we feel, are due to a disturbance

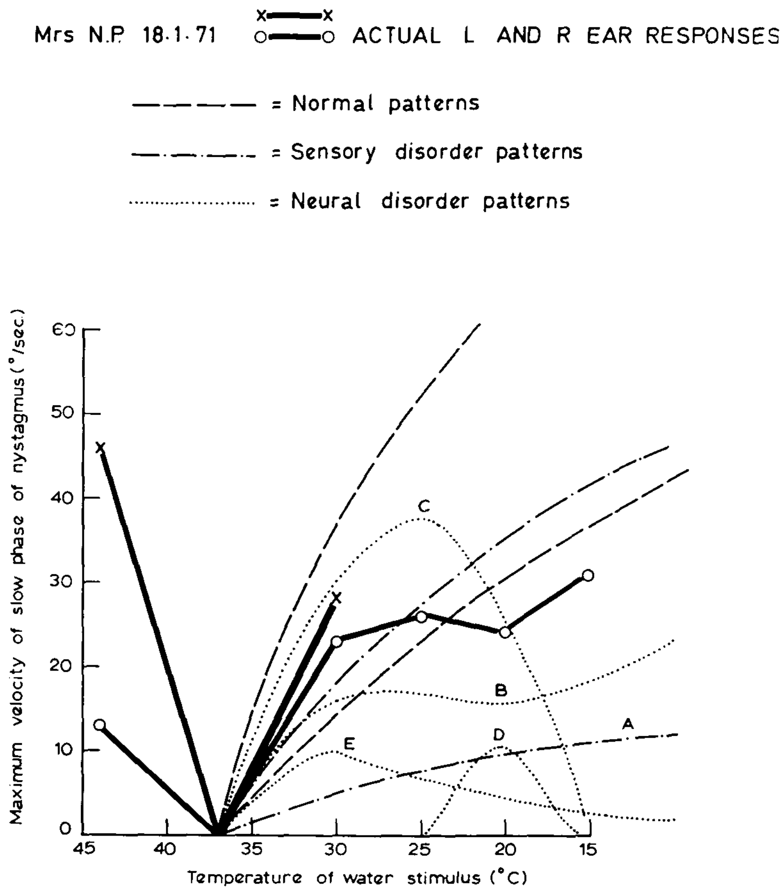

FIG. 7.
Caloric tests and thermal vestibulometry.

of nerve fibre conduction generally rather than of the central nervous system specifically, and therefore the term 'neural' has been used to describe them.

Some cases of primarily neural pathology, e.g. an VIIIth nerve neuro-fibroma, appear to masquerade as a sensory disorder however, as may also occur in disturbances of auditory function, presumably because a secondary disturbance of labyrinthine blood supply or a direct extension of the pathological process to the labyrinth produces damage to the sensor of a degree which is sufficiently more severe as to dominate the pattern of response to tests. But a dominance of sensory signs in a primarily neural case does not necessarily affect both parts of the auditory/vestibular system; in one case of acoustic neuroma seen recently the auditory signs were of neural type of disorder but the vestibular signs were more suggestive of a sensory lesion. In general though, and in the case of Mrs. N. P. illustrated here, our experience is that at least some cases with peripheral neural lesions show the diagnostically highly significant neural pattern of response. More work needs doing on this technique before its clinical usefulness can be assured. The obvious snag is the inordinate amount of time needed for it, but for selected cases meriting the time needed it seems to us to be most promising.

Electrophysiological and other forms of objective audiometry

There are various electrophysiological measurement techniques which are, or are liable to be, within the scope of audiological practice. When used, they often provide great diagnostic benefits either in differential diagnosis of site of disorder or in objective measurement (i.e. not dependent on a voluntary response by the patient) of the function of certain components, or series of components, in the auditory system. Their scope is limited, however, to components in the range from middle ear to cerebral cortex and none of them provides a complete measurement of hearing.

Thus, they may not indicate any abnormality in the pathways from ear to brain, yet this does not necessarily imply that the auditory signals, transduced to neural events and then transmitted to the brain, result in a consciously perceived sensation. For instance, in hysterical, autistic or aphasic patients the auditory signals may evoke an electrical response in the cerebral cortex but the patient may still be 'deaf' in the ordinary sense of the word, in that he appears not to hear auditory signals in circumstances that normal persons of the same age and development could be expected to hear. But what does 'hearing' and 'deafness' really mean? Most medical and audiological definitions, and the ones used in our own clinical work are more restricted than the everyday usage of these words and stop after the level of consciously perceived auditory sensation. Thus, a hysteric with a loss of conscious auditory sensation could correctly be described as having a hysterical deafness; on the other hand an autistic or aphasic, who was thought to perceive sounds consciously at normal intensities but whose disability was a failure to recognize and understand sounds, would appear not to hear sounds yet would not be truly deaf according to the definition given above. The problems of semantics as well as the limitations of the tests themselves complicate the task of accurate and understandable reporting of the results of objective audiometry. One is forced to such long-winded expressions as 'whilst the clinical appearance was one of deafness, the evoked response audiometric thresholds were normal; it seems likely that the disorder is either a functional deafness or an impairment of recognition and/or understanding of sounds.'

In clinical interpretation, and especially in medico-legal interpretation of objective audiometric tests, one must therefore exercise great care in choice of words used to describe what these tests have revealed. This, in turn, depends on careful consideration of what parts of the auditory system each objective test procedure has in fact tested. A useful schematic diagram to aid this is shown in Fig. 8. This is a modification of the

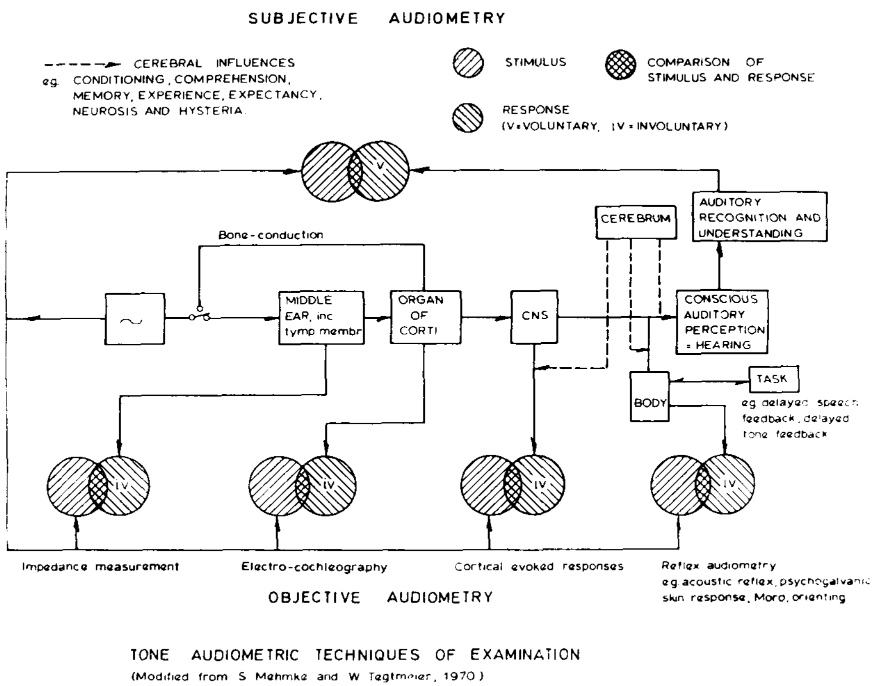

FIG. 8.

Objective and subjective audiometric tests in relation to components of the hearing mechanism (modified from Mehmke and Tegtmeier, 1970).

scheme published recently by Mehmke and Tegtmeier (1970) and embodies most of the objective tests applicable to clinical audiology.

Much has been written and spoken about evoked (or electrical) response audiometry (E.R.A.) in recent years, and as this has not already been described in this paper, it is relevant to expand on it slightly now. Strictly the term should have 'cortical' preceding it as there are a whole range of auditorily evoked responses which can be utilized for audiometric purposes, e.g. an involuntary movement, a change in skin resistance, an acoustic reflex, an VIIIth nerve action potential. Others have used more precise terminology such as electroencephalographic (E.E.G.) audiometry or evoked vertex response audiometry, but for the purposes of this paper the procedure will be referred to simply as E.R.A.

The principal clinical uses of E.R.A. can be summarized as providing an objective audiometric measurement in those who cannot or who will not respond voluntarily to conventional audiometric procedures. The 'cannot' variety is comprised mainly of infants and young children, and the 'will-not' category mainly of older children or adults with non-organic hearing loss. Whilst the test is nearly always successful in the latter, it has provided many disappointments in the former.

There are three main problems with E.R.A. in children. The first two affect all types of children; their E.R.A. patterns have greater inter- and intra-subject variability, and the children tend quickly to become bored and either go to sleep or start to fidget. This alters the E.E.G. pattern which, respectively, may upset the quantitative value of the E.R.A. or provide so many transients in the E.E.G. and artifacts in the summed evoked responses as to render them difficult or impossible to interpret. The third problem is that the kinds of child for whom E.R.A. has the greatest potential value, because of difficulty in testing by conventional paedo-audiological techniques, are those children with central nervous system disorders either causing their apparent deafness or complicating an auditory system lesion. Again these may be so hyper-kinetic or have such abnormal E.E.G.s anyway that E.R.A. provides little if any reliable additional information on them. In our experience, about one-third of the children referred for E.R.A. fall into this group. In another third, the tests provide rather limitedly useful information, sometimes little more than confirmatory to conventional assessments, In the last third, however, E.R.A. has provided information of the greatest value.

It is hoped that current research, in our laboratories and in many others in this country and overseas, will improve further the clinical value of E.R.A. in children. But one aspect is already quite clear and will not change. Whilst E.R.A. can be a most powerful and valuable technique for audiometry in children, it cannot and must not take the place of any of the more conventional methods of paedo-audiological assessment; it can usefully supplement them, not replace them.

The same usage, and limitations imposed by expense, time and skills, seem likely to apply to the still newer technique of electrocochleography (E.Co.G.). In this, electrodes in or around the ear pick up the VIIIth nerve action potentials resulting from auditory stimuli delivered to that ear. These are then amplified, analysed and displayed. With advanced computational analysis, the cochlear microphonics may also find clinical usage.

The type and siting of electrodes used in E.R.A. and E.Co.G. is shown diagrammatically in Fig. 9, and in the case of E.Co.G. the associated source of acoustic signal is also indicated. For E.R.A., the signal can be a tone burst of known frequency, intensity and duration, and can be given by loudspeaker, earphone or bone conductor; and masking of the non-test ear can be used where appropriate. Also, non-acoustic signals using other sensory modalities, such as by light-flash or tactile stimuli, often have great value in differential diagnosis between purely auditory system and more generalized central nervous system disorders. The procedure suffers however from the problems already described, which

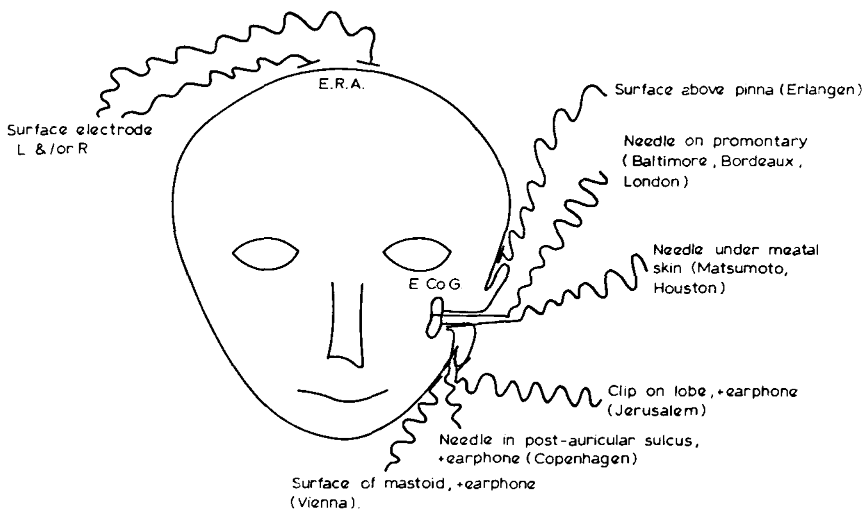

FIG. 9.

Site of active electrodes in cortical evoked response audiometry (E.R.A.) and electro-cochleography (E.Co.G.).

are related to any factors influencing the E.E.G.; the latter include sedatives, anaesthetics, sleep, fidgeting, hyper-kinesia, and central nervous system disorders.

E.Co.G. on the contrary is more or less independent of these cerebral influences and there is no need for masking of the non-test ear. But as yet it is much less accurate quantitatively in relation to the intensity and frequency of the stimulus, and it is limited to the air-conduction route of stimulation. Stimuli are usually clicks, or at best frequency-filtered clicks. Bone-conduction stimuli may eventually become possible, but in the present state of the art the responses would be obscured due to the microphonic effects associated with the direct vibration of the electrodes. Nevertheless, E.Co.G. has great differential diagnostic potential, especially if the associated electrophysiological and computer technology develops to allow greater use of the clinically more acceptable surface electrodes, also of the bone-conduction route of stimulation, and possibly of the cochlear microphonic responses as well.

Conclusion

I may be criticized, quite rightly, for complicating the ordinary clinical audiological test procedures which may have seemed up to now to be quite simple, reliable and sufficient. But I am quite unashamed of this because in fact all I have done is to illustrate that audiology, indeed quite often even the basic procedures, is complex. But audiology, and vestibulometry, have potential diagnostic advantages that reach far beyond their currently rather limited role in the majority of hospital clinics, the limitation being enforced by the present organization of audiology in the National Health Service.

The potential benefits consist not only of a general extension of diagnostic procedures which would appreciably reduce the proportion of patients in whom diagnosis is uncertain, but also of a much greater precision in application and interpretation of those techniques already in use. For the former, persons of scientific officer level and specialized facilities would be needed, perhaps on a regional basis. The latter involves provision of more staff generally in order to allow more time for a proper audiological investigation, which of itself means increases in space, equipment and remuneration, together with a drastic elevation of the minimal and/or inexpert training that many audiology technicians at present receive; it also includes introduction of advanced training courses for and posts of, at least, technical officer status.

I hope, therefore, that I have been successful in this lecture in so illustrating the diagnostic advantages to be gained that you will consider the complexity, additional staff, equipment and facilities to be more than justified. My hope for this success is because I am convinced that present-day, and future, audiology has a very worthwhile place in the clinical practice of otology. I am therefore most grateful for this opportunity of outlining the various fields in which modern audiology, including vestibulometry, really has a very great deal to offer you and your patients.

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