A new high-frequency audiometer

by

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Tinnitus (TI) is held to be a symptom that is usually associated with hearing losses of various origin (Chaba, 1982). This notion was, at least partially, supported by Berlin. In a number of patients with TI, who did not show hearing losses on discrete-frequency audiometry, he demonstrated small circumscribed losses at between-frequencies by means of Békésy audiometer with a continuous-frequency sweep. Berlin then proposed that in some other patients, in whom hearing losses are not evident, these may be located in the high-frequency region, beyond the reach of conventional audiometry, i.e., beyond 8 kHz.

There are other problems that would make audiometric examination in the high-frequency region desirable; for example, the monitoring of the audiometric status of patients receiving ototoxic antibiotics or diuretics. Histological examination (Schuknecht, 1974) demonstrated that in such cases hair-cell degeneration starts at the very basal end of the cochlea, i.e., at the highest frequencies. Hence, high-frequency audiometry should give the earliest possible warning. When the degeneration has progressed down into the 4–8 kHz region, i.e., can be assessed by conventional audiometry, it is usually too late to halt the functional deficit by stopping the medication in question.

Acoustically, high-frequency audiometry is difficult, if not impossible, to execute. Above 6–8 kHz, the usual pre-calibration of earphones becomes increasingly unreliable as the quarter wavelength approaches the length of the ear canal, setting up resonances. This shortcoming can only be overcome by sophisticated instrumentation, involving the placement of probe microphones deep into the ear canal, close to the tympanic membrane for direct monitoring of the sound pressure level (Stevens *et al.*, 1982). Above approximately 15 kHz, even such techniques are no longer of any help as the wavefront impinging onto the tympanic membrane is not uniform any more. Sampling the sound pressure at one spot by a probe microphone is to no avail. One would have to integrate the sound pressure over the entire tympanic-membrane surface, obviously a technical impossibility.

There is an alternate approach that avoids the use of acoustic signals with their shortcomings altogether: to employ electrical signals. The use of electrical signals that elicit auditory sensations has a fairly long history. In the 1920s, several groups of investigators were interested in the phenomenon of so-called electrophonic hearing. [For literature, Flottorp, 1953]. The ear canal was filled with a physiological salt solution, into which a wire was immerged that served as the active electrode. The indifferent electrode was connected to the forearm, for example. Audio-signals applied to this electrode pair could be heard by the subject, but there was strong second-harmonic distortion. The latter could be eliminated by a dc bias of several volts. Since the bias had to be re-adjusted for each signal frequency, since the phenomenon

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https://doi.org/10.1017/S1755146300090235 Published online by Cambridge University Press

was limited to frequencies below approximately 2 kHz and since the dynamic range was not wider than 10–15 dB, the system was not really suited for the transmission of a wide range of frequencies, e.g. speech signals.

When, however, the audio-signal is used to modulate a high-frequency carrier (60–80 kHz) and when the combined signal was applied *via* a pair of external, stainless steel electrodes, one of them placed onto either mastoid, it became indeed possible to put the audio-signal 'under the skin'. This method was first employed in the 1960s (Puharich and Lawrence, 1969) but for purposes that need not concern us here, since their rationale was eventually proven erroneous. What was striking even at that earlier time was the high fidelity of speech signals, i.e., the capability of the method to carry broad-spectrum signals into the ear, including high frequencies. R. Dugot, who designed the device used currently, also designed and built some of the earlier instruments.

The currently-used instrument functions essentially as follows: There are two frequency generators, one at the carrier frequency, 60 Hz at present, although it is planned to use eventually a higher frequency of about 100 kHz. The second generator is tunable and may be tuned to any frequency between 1 and 20 kHz. (There is no principal hindrance to the use of other frequencies, lower as well as higher ones; for the present purpose they were not felt to be needed.) Modulation, not exceeding 90 per cent to avoid overmodulation and the attendant audible distortion, is achieved in a modulator stage. This is followed by an interrupter switch, an attenuator and an amplifier; finally the signal is led to a pair of stainless-steel electrodes, 2 cm in diameter. They are applied, one to either mastoid, for simultaneous bilateral testing or to one mastoid and the forearm for unilateral testing. The electrodes are mylar-coated, i.e., capacitative coupling is used. In this situation the subject's head becomes part of a resonant circuit in series with the mylar-coated electrodes and output indicators. The magnitude of the input signal can be precisely determined by knowing the Q-factor of the system, the distance of the test frequency from the resonant frequency and the magnitude of the input signal. The voltage at the electrodes is held constant at 5 v p-p, i.e., at 1.77 v RMS. Sensation magnitude is solely determined by the current strength that, at threshold in the middle-frequency range, varies between individuals and for different frequencies between 1 and 10 milliamps. The dependence on current is quite logical. If in the mechano-acoustic domain the sensation magnitude is given by the applied sound pressure, in the electrical domain it must be given by the applied current (Olsen, 1940). At present, maximal currents do not exceed 25 ma for reasons of safety considerations.

With the voltage at about 2 v RMS and currents as listed, the total electrical power applied to the head in the middle frequencies does not exceed 20 mwatts, and even at maximal output settings of 25 ma the power is only about 50 mwatts. These values are still within safe limits (I.R.D.C., 1983), especially when one considers the short duration of auditory test signals, which usually is less than 1 s. Moreover, if the mylar coat should ever become defective so that the current would go directly to the skin, the resonant circuit detunes immediately and the voltage is reduced to insignificant levels.

The reader may be interested in some performance data of the instrument and the conclusions one may draw on their basis.

1. Fig. 1 shows the electrical audiogram above 1 kHz, expressed in ma, of a subject with an upper auditory limit at about 18 kHz. This in our present experience represents excellent high-frequency hearing. The upper limit is of course partly determined by the maximal current setting, 25 ma in the present case, but the precipitous decline of the curve above 16 kHz indicates its reality. In other subjects tested, the upper limit varied from 18 kHz down to about 10 kHz. The importance of these findings lies in the fact that all subjects had to be considered to have hearing 'within normal limits' on the

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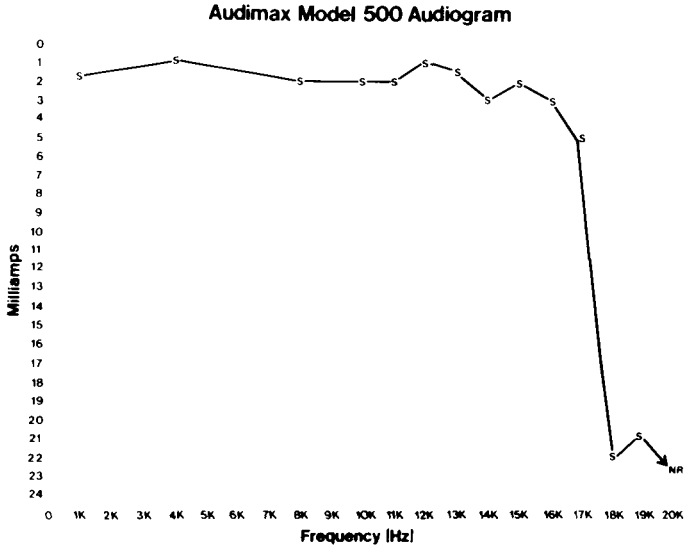


FIG. 1

Audiogram (milliamps vs. frequency, both in linear units) of a 22-year-old individual with normal hearing in the standard audiometric range.

basis of their hearing levels up to and including 8 kHz.

2. On two trained subjects, the magnitude of electrical signals of various frequencies applied to one mastoid (the second electrode being on the forearm) was adjusted so that they appeared equally loud compared to an acoustic signal of 1 kHz presented to the other ear. The level of the acoustic signal was gradually raised in steps of 5 dB starting at threshold. When the results were plotted in double-log fashion, i.e., decibel milliamps vs hearing levels, the resulting curves ran almost straight, but with a slope of about 1:3.5 (Fig. 2). This finding confirms the well-known fact that the sensation magnitude elicited by electrical signals progresses at a much faster rate than that elicited by acoustic signals (Stevens, 1957). It also permits to plot results of electrical testing conveniently in decibels. However, the shape of the curve in Fig. 1 that was given in milliamps and linear frequency values was not materially affected by the decibel plotting. Its downward slope just ran even steeper.

3. Next, the mode of reception of the electrical signals was examined. Since sine-wave signals elicited pure-tone sensations, the reception can only be cochlear, for neural excitation does not yield pure-tone sensations, especially not at high frequencies, as the experience with cochlear protheses indicates.

4a. The occlusion of one ear canal let the signal lateralize into that ear. Therefore, the mode of stimulation must be predominately by bone conduction. This statement is made with some hesitation: (i) localization was not always all the way into the occluded ear, but, especially at higher frequencies, only toward that ear; (ii) even signals as high as 4 kHz showed some lateralization.

b. In a patient with otosclerosis, but good bone conduction in the worse-hearing ear (Fig. 3, top), the electrical audiogram, given in decibels, was reasonably close to that of our normal group (Fig. 3, bottom). It was definitely better than what one should have expected on the basis of the air conduction audiogram (Fig. 3, top), which supports the above statement.

There was one unexpected finding: the small loss for electrical stimulation at 8 kHz

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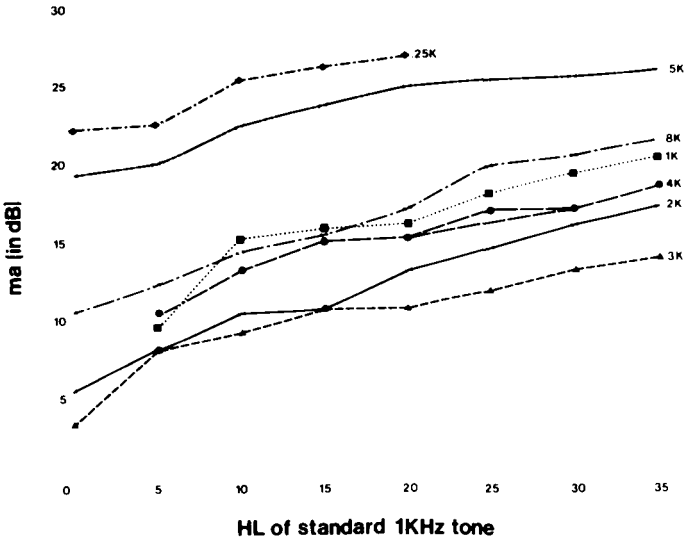


FIG. 2

Equal loudness between seven electrical test tones (0.25 – 8 kHz), given in db-ma, with the hearing levels of a standard 1 kHz tone offered by air conduction to the opposite ear. For presentation of the test tones, one electrode was applied to the mastoid of the ear to be tested and the other to the forearm.

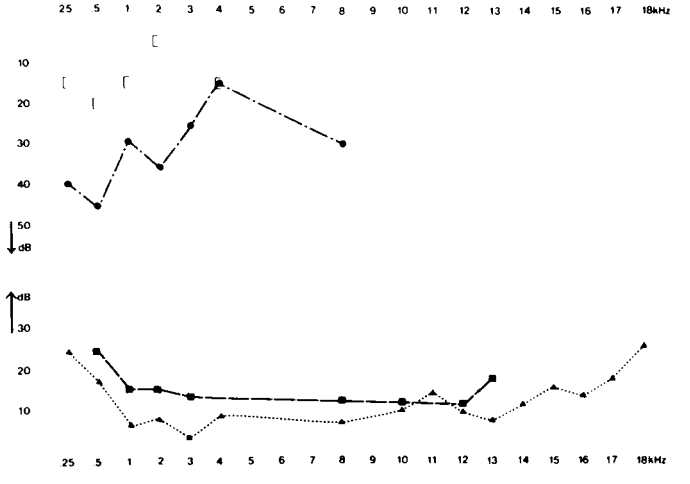


FIG. 3

(Top) Air conduction (solid circles, dot-dashed line) and masked bone conduction (angled brackets) audiogram for the poorer-hearing ear of a 54-year-old female patient with otosclerosis. (Bottom) The electrical audiogram (solid squares, dashed line) of the same patient compared to the average (solid triangles, dotted line) of six normal-hearing individuals.

(Fig. 3, bottom). The audiogram (Fig. 3, top) showed a 30 dB loss at that frequency. That and the age of the patient (54 years) might have suggested a beginning presbycusis, an interpretation that, on the basis of the electrical audiogram, appears to be incorrect. This finding confirms the opinion long held by one of the authors

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(J.T.), i.e., that the air-conduction losses frequently seen at 4 and 8 kHz after surgical middle-ear reconstruction do not necessarily reflect cochlear impairments, but conductive ones, most likely caused by a slight shortcoming of the surgical procedure. This had been frequently observed in animal experimentation (Tonndorf, 1982). Electrical testing could decide the issue in a given patient, especially since bone-conduction signals do not reach as high as 8 kHz.

The finding that hearing in response to electrical signal is mediated by bone conduction is in sharp contrast to an earlier one made by one of the authors (Tonndorf, 1959). A group of unilateral otosclerotics was tested for electrophonic hearing. All subjects could hear the signals in their normal ear, but none of them in their otosclerotic ear, suggesting that stimulation requires a normally-functioning middle ear. For this reason, the term electrophonic hearing does not apply to the mode of signal presentation as currently used. Therefore, the more neutral term electrical hearing was chosen.

It is hoped that the present paper indicates the usefulness of electrical auditory testing in the high-frequency region that is beyond the limits of conventional acoustic testing. Furthermore, it was demonstrated that reception of the electrical signals is cochlear and that signals are mainly transmitted by the bone-conduction route.

Note: The instrument used in the present experiments is a prototype designed by R. Dugot, design engineer of Audimax, the company, at which it was built. Commercial production and marketing will commence shortly.

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