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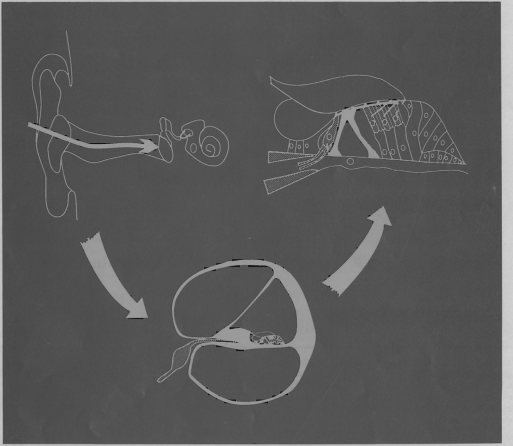

- Ear as Transducer
- Hair Cells
- Otoacoustic Emissions
- Cochlear Implant

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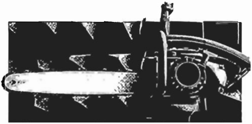

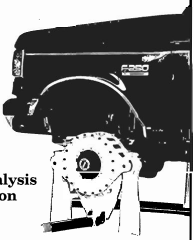

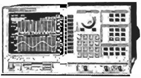

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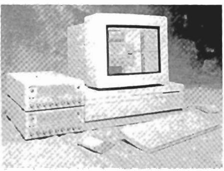
COVER : *The image on the cover illustrates the basic elements of the human auditory system - see paper by Yates.*



Editorial

About once each year we publish a Special Issue in which invited contributors survey a field of particular interest in acoustics. The subject of Hearing is central to our whole discipline -- indeed, without this particular biological sense, acoustics as a subject would hardly exist! Because of this central importance and the wide scope of the field of hearing, we could have approached it in many different ways, and perhaps some of these will be the subject of other special issues in the future. This time we have concentrated on physiological aspects of human hearing, and our invited papers come from four Australian groups that have made very significant contributions to knowledge in this area. The first two papers deal with the physiology of normal hearing, and follow the path from the eardrum through the cochlea to the hair cells and the neural output signals. The next contribution examines the clues that are provided by the spontaneous oscillation of the inner ear itself, while the final paper reports on the exciting progress that has been made in development of a cochlear implant to aid the profoundly deaf. It is clearly impossible for a single issue of our journal to give a comprehensive treatment of these complex matters, but the aim has been both to sketch in the general background and to indicate the frontiers of current research.

Letters to the Editors are invited on any relevant matters.

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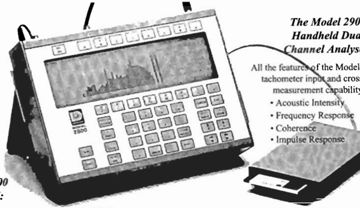

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The Ear as an Acoustical Transducer

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Abstract: Biology has imposed several severe limitations on the ear in evolving as the biological equivalent of a microphone. Speed of response, dynamic range and sensitivity are all limited by the raw materials of the nervous system. In adapting to overcome these limitations, the ear has developed some unique solutions that enable it to perform as well or better than many commercially available microphones.

1. INTRODUCTION

The ear has the task of translating incoming acoustic signals into a neural code suitable for transmission to the brain. To accomplish this it converts fluctuations in air pressure, which are the signals of interest, into electrical pulses and faithfully transmits to the central nervous system all aspects of the sound that are of concern to an animal for its survival. In this respect the cochlea, or inner ear, has many parallels with a microphone, but it has limitations imposed upon it that demand a very innovative design. This paper will consider those factors that pose problems for the cochlea and will illustrate the techniques that have enabled evolution to overcome those restrictions.

1.1 The Anatomy of the Ear

The most obvious anatomical characteristic of the ear, the pinna (Fig.1.A), is simply an external structure to define and protect the external ear canal, although it may also have a role in direction detection for high-frequency signals. The ear canal conducts sound to the eardrum which, together with the small articulated bones of the middle ear, acts as an impedance transformer to couple the low-impedance air medium to a higher-impedance hydro-mechanical system in the cochlea. It is within the cochlea, or inner ear, that the true transduction takes place and it is with the cochlea alone that we are concerned here (1).

The cochlea is a very small coiled structure with a three-chambered cross-section (Fig.1.B). The three chambers, scala vestibuli, scala media and scala tympani are each separated by thin partitions and are filled with dilute water solutions of sodium or potassium salts. Separating scala vestibuli from scala media is a thin, cellular membrane known as Reisner's membrane, which separates the high-sodium, low-potassium aqueous solution of scala vestibuli from the low-sodium, high-potassium solution of scala media. Scala tympani is filled with the same solution as scala vestibuli.

Separating scala media from scala tympani is the basilar membrane, a narrow ribbon-like structure carrying the cells of the sensory structure, the Organ of Corti. The basilar membrane is elastic and when displaced returns

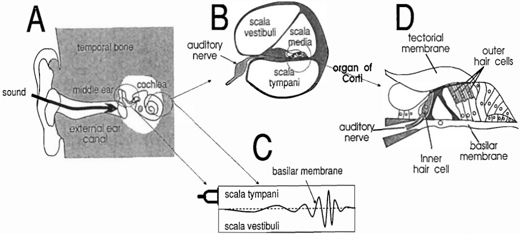

Figure1. The relationship of the cochlea to the external components of the ear. The cochlea is embedded in the hard temporal bone (A). It is a long, spiralled chamber, subdivided along its length into three chambers (B) Two of these chambers, scalas media and tympani, are separated by the basilar membrane. Acoustic displacement of the middle-ear bones causes a travelling wave to propagate along the basilar membrane, shown diagrammatically in (C). Displacement of the basilar membrane stimulates the receptor cells of the organ of Corti which rides on the basilar membrane (D).

immediately to its equilibrium position, but it is stiffer near the input (basal) and floppier near the far (apical) end of the cochlea. Displacement of the middle ear bones results in displacement of the basilar membrane near its basal end. This disturbance is propagated through the fluid to the adjacent regions of the membrane which are in turn displaced. Hence, the original disturbance of the middle ear is carried along the membrane by an interaction between the elasticity of the membrane and the inertia of the fluid.

The mechanical disturbance is propagated down the cochlea in the form of a travelling wave, very much like a wave on the surface of an ocean (Fig.1C). The differences are two-fold, however: (i) instead of occurring at an air-water interface as the ocean wave does, the cochlea travelling wave occurs at the interface between two water-filled regions separated by a membrane, and (ii) unlike the surface of the ocean, the basilar membrane has its own mass, and consequently, inertia. The first difference is not significant for the physics of the travelling wave, the second has a profound effect. At any place along the membrane there is a high-frequency limit above which the inertial reactance of the basilar membrane dominates its elastic reactance so that the reaction of the membrane on the adjacent fluid changes sign. For all higher frequencies the travelling wave cannot propagate at this place: it decays as an evanescent wave. Because the elastic properties of the membrane are tapered along the cochlea, this characteristic cut-off frequency varies according to the position along the cochlea, basal regions having higher cutoff frequencies.

Thus, when the middle ear is disturbed by a complex signal, a travelling wave is produced on the basilar membrane, with high-frequency components of the signal travelling only a short distance before stopping and with low-frequency components travelling almost the full length of the cochlea.

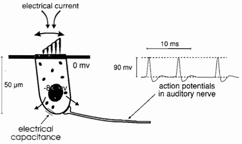

Figure 2. Basic mechano-sensitive transducer in biology. The hair cell is a specialised cell containing small cilia which protrude from one end of the cell. The cilia normally pass a standing, or bias, current. Displacement of the cilia to one side reduces the current while displacement to the other side increases it. Increased current flow reduces the (negative) trans-membrane potential, in turn releasing a chemical transmitter from the synapse. The transmitter produces action potentials in the nerve fibre. Electrical capacitance slows voltage changes and reduces the bandwidth of the system.

1.2 The Raw Materials of Hearing

In effect, all the mechanical structures within the cochlea exist solely to stimulate the sensory cells which are distributed along the length of the basilar membrane.

The cells of the Organ of Corti ride on the basilar membrane and are displaced along with it (Fig.1D). As they are disturbed by the motion, the sensory cells are stimulated to produce changes in their internal electrical environment and, in turn, these excite the nerve endings attached to them, generating action potentials for transmission to the brain.

1.2.1 Mechanically sensitive cells

Mechanically sensitive cells are basically the same across species (Fig.2). They consist of a cell body with small hairs protruding from the top. Like cells of all types, their insides are at an electrical potential difference from outside, so that the inside is around 40-80 millivolts more negative. A small bias current flows continuously through the tops of the hairs, down into the cell body, and out through the cell wall. Displacement of the tips of the hairs modulates the bias current, resulting in a variation of current flow through the cell in sympathy with the displacement of the hairs. In turn, the voltage across the cell wall also varies in analogy with displacement, much like a microphone; in fact the current, when measured as a small voltage drop outside the mammalian cochlea, is known as the cochlear microphonic and may be replayed through a loudspeaker with surprising fidelity to the original sounds.

1.2.2 Slow responses

The problem for transduction lies in the relatively large electrical capacitance of the cell and the small currents which flow (2). Fast modulations of the current caused by rapid displacements of the hairs are smoothed out by the capacitance, with the result that the membrane voltage preserves only the slow component of the signal. Typical time constants are about 200 µseconds or greater, restricting the frequency response to below 800 Hz. This is too slow to be of much use to an animal in gleaning information from a noise produced by a predator or prey.

1.2.3 Limited dynamic range

A second problem lies in the next stage of transduction: the conversion to neural impulses, or action potentials. At the base of hair cells are small structures known as synapses which release packets of chemical transmitter in response to membrane voltage changes. The transmitter in turn causes action potentials, short electrical pulses of about 100 mv amplitude, to propagate away from the cell towards the brain. It is the rate and timing of these action potentials which carries information to the consciousness of the animal, basically in the form of a pulse-rate code. Louder sound means more action potentials per second. The upper limit to the rate at which action potentials may be generated, however, is around 300/sec and the minimum useful lower rate is of the order of 1/second. (The pulses in the auditory nerve are not regular but occur randomly with only the average rate being meaningful. Thus, interval timing may not be used.) This limits the range of intensities which may be coded to only 300:1, or about 50 dB and even less in practice, about 90 dB short of the full auditory range.

1.2.4 Inadequate sensitivity

A third problem exists in the sensitivity of the hair cells. Threshold acoustical pressures produce displacements of the eardrum of around 10^{-12} m while hair cells require displacements of the order of 10^{-8} m. To reach maximum sensitivity requires a mechanical amplification of around 10,000 times.

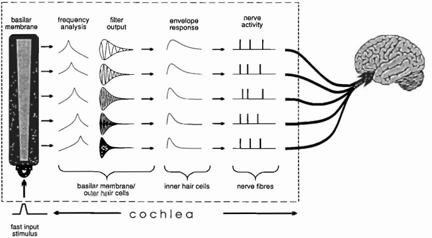

Figure 3. Diagrammatic representation of how the cochlea transforms an incoming, wide-band signal into a number of parallel, narrow-band signals.

2. THE SPEED PROBLEM

The cochlea has evolved an extremely elegant way of overcoming the limitation on speed imposed by the electrical capacitance of the hair cells and the slow pulse rate of the neurones. Essentially, it encodes the incoming single, wideband signal into a large set of parallel, narrowband channels, each coding a different region of the incoming bandwidth (Fig.3).

Recordings of nerve fibre responses to bursts of pure sinusoidal sounds showed that individual fibres are stimulated best, i.e., increase their firing rates in response to the softest sounds, when the stimulus frequency matches some frequency characteristic of the fibre. That is, for a given fibre there is a characteristic frequency (CF) at which it is most easily stimulated; frequencies either side of the CF require greater intensities before they respond. In effect, each nerve fibre is preceded by a narrowband filter which limits it to responding only to a narrow range of frequencies, at least at low intensities. Fibres coming from different regions along the cochlea have different, tonotopically organised CFs and respond to the envelope of the vibrations of their associated filters (Fig.4).

Since each filter is narrow enough that its characteristic ringing time is of the order of a few milliseconds, any response at all by the filter is sufficiently slowed as to give the hair cell and neurone time to respond. Thus, a short, rapid fluctuation in pressure, too fast to affect a simple nerve fibre, will set a range of filters ringing and their attached nerve fibres will increase their firing rates according to the amplitude of the ringing in each filter.

Recent measurements have shown that the cochlear filters exist in the form of tuned mechanical responses by the basilar membrane (3,4,5). For any given stimulus frequency there is a place along the cochlea at which the basilar membrane vibrates with greater amplitude than elsewhere. Hair cells riding on the basilar membrane at that location are then stimulated at lower intensity levels than are other hair cells.

3. THE DYNAMIC RANGE PROBLEM

The second problem, concerning the dynamic range of the cochlea, is solved by dynamic compression of the range of vibration amplitudes on the basilar membrane. At low intensities, say below 30-40 dB SPL, the vibration amplitude of the basilar membrane is linearly related to the amplitude of the acoustic pressure changes, but at higher intensities the basilar membrane amplitude grows much more slowly, somewhere between 0.5 dB/dB and 0.05 dB/dB (Fig.5). In effect, an automatic gain control loop becomes operative, restricting the growth in the basilar membrane vibrations to less than the growth in sound level. Thus, hair cells and nerve fibres riding on the basilar membrane are not driven proportionally as hard at high intensities as at low (6,7,8).

The compression operates over a restricted frequency range, however, around the CF for any given place. Thus, the apparent frequency selectivity of any nerve fibre is also reduced as the intensity grows.

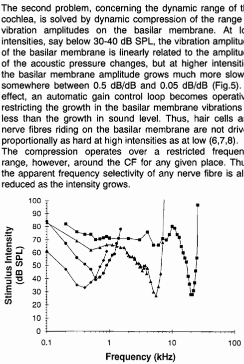

Figure 4. Tuning curves recorded from four nerve fibres emmanating from different places along the length of the cochlea. The curves represent the sound intensity required to increase the firing rate of the nerve fibre by a just perceptible amount, i.e., they represent the input level necessary to produce a constant output. As such, they are like inverted filter shapes. The frequency of best senstivity is, for each fibre, known as its characteristic frequency, or CF. Each fibre forms an element of a Fourier analyser.

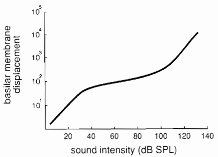

Figure 5. Basilar membrane input-output function at the characteristic frequency. This curve relates the amplitude of the guinea pig basilar membrane vibration to the intensity of the incoming sound, for a single-frequency tone. For low SPLs the membrane displacement grows linearly with SPL. At around 30-40 dBSPL the membrane enters a nonlinear state and the amplitude grows by around 10dB for a 60dB increase in SPL. At higher intensities the growth becomes linear again.

4. HOW IS IT DONE?

Recent research has shown us something of how the cochlea accomplishes this preprocessing of the stimulus, and the answer is implicitly associated with the third problem, that of sensitivity.

4.1 The Mechanical Amplifier

In 1978, David Kemp of the Institute of Laryngology and Otology in London demonstrated (9) the surprising fact that ears could talk back! When he delivered short clicks into the external ear canals of human subjects he was able to record a very soft echo which, further experiment showed, was clearly coming from within the cochlea. Research since then has shown that this echo apparently results from a mechanical amplifier within the cochlea, amplifying the mechanical vibrations of the basilar membrane by as much as a thousand times, and other research has implied that the agents responsible for the amplification are the outer hair cells (Fig.1D), an array of cells similar to the sensory receptor cells, the inner hair cells but without strong neural connections to the brain. When stimulated by mechanical movement of the basilar membrane, they apparently 'kick back' in some way and in just the right phase to overcome most of the friction damping the vibrations, thereby increasing the basilar membrane vibration enormously. It was minor mis-coordinations of the outer hair cells that Kemp was recording as an echo. Acoustic energy of various frequencies from the click would enter the cochlea, travel to its appropriate place of amplification and be amplified with the assistance of the outer hair cells. Slight variations in the magnitude and timing of the amplified responses then travelled back along the basilar membrane to re-emerge from the cochlea.

4.2 Frequency Analysis

This trick of positive feedback enhances the amplitude of the basilar membrane travelling wave as it rolls down the cochlea to approach the place with a matching CF (3,4,5). For reasons which are unclear as yet, the feedback works best close to the place of CF; the enhancement occurs only close to the CF region and results in a peak in the amplitude of the wave just before it reaches the cutoff place and falls rapidly again. The resultant amplitude distribution resembles a band-pass filter with a bandwidth of around one kilohertz and with very steep sides and deep skirts.

Thus, in one action, the outer hair cells mechanically amplify the travelling wave and help analyse it into its respective frequency components.

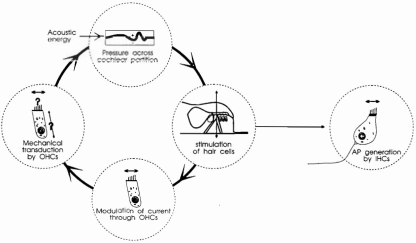

Figure 6. Positive mechanical feedback amplifies the displacement amplitude of the basilar membrane. Acoustic energy enters the cochlea via the middle ear. The consequent pressure change produces a displacement of the basilar membrane which travels down the cochlea. Displacement of the basilar membrane causes shearing between the hair cells and the tectorial membrane, thus tilting the cilia of the hair cells and modulating the current through the hair cells. At some place characteristic of the input frequency the hair cells produce a mechanical moment of their own, which feeds pressure back into the cochlea fluids. This pressure is of the correct phase to assist the displacement of the membrane, thus completing the loop. The inner hair cells are also carried along on the basilar membrane and stimulate action potentials in the auditory nerve.

4.3 Amplitude Range Compression

The properties of negative-feedback systems are well known but positive-feedback results in some quite contrary behaviour. Negative feedback acts to reduce the effect of small changes in the characteristics of system components, while with positive feedback even small changes in component behaviour are amplified to become dominant in system behaviour.

This is well demonstrated in the action of the basilar membrane, as we and others have shown (4,8). The outer hair cells, which provide the mechanical energy to amplify the motion, are themselves nonlinear (Fig.7). For small amplitudes of displacement they appear to respond by producing a mechanical force proportional to basilar membrane displacement, but for larger movements, of the order of 100 nanometres, the force produced falls off, saturating at around 200-300 nanometres displacement (10,11). What this implies for the positive feedback is that the amount of feedback, and hence (disproportionately) the amplification of the basilar membrane motion, falls off at higher stimulus intensities. In effect, the growth of the basilar membrane with intensity is nonlinear above a few tens of nanometres (7), rising only at a rate of around 0.5 dB/dB to 0.05 dB/dB. Furthermore, since the positive feedback works only close to the CF place, the nonlinearity appears only near that place and so the shape of the filter changes with intensity.

Hence, the outer hair cells amplify only if the basilar membrane motion is at or below the middle of their range of best sensitivity. It is no coincidence that this is also precisely the middle of the amplitude range of the inner hair cells, since the two types of cell are derived from one another. Thus, the motion of the basilar membrane is strongly amplified if the amplitude is below the optimum for the sensory cells, and then progressively less amplification occurs as the stimulus becomes louder. It is, in effect, a type of automatic gain control operating to keep the sensory cells in their optimum operating range.

5. SUMMARY

Although called upon to perform somewhat the same functions as a microphone, the ear has been disadvantaged by the raw materials of biology: the receptor cells and the nerve itself. Response to fast acoustic signals is limited primarily by the electrical capacitances associated with the membranes defining the limits of the cell, which restrict responses to slower than a few hundred microseconds at best. The range of intensities which such cells can handle before saturation is also limited in biological transducers, usually to around 20-30 dB. Finally, the displacement amplitudes of air particles at lower SPLs are much smaller than the amplitudes required to elicit discernible responses in mechanically sensitive cells, so some amplification is required. Furthermore, the imprecision of biological dimensions means that no design can be relied upon if it requires close control of tolerances: designs must be inherently self-regulating so that they will work in spite of significant variation in size and shape. Nature has overcome these problems by some very clever mechanical preprocessing, including some radical solutions not typically seen in engineering design.

The speed limitation has been overcome by partial Fourier analysis of the acoustic signal and detection of the envelope of each frequency band. Thus, a single wideband input is converted to many, parallel, narrow-bandwidth channels.

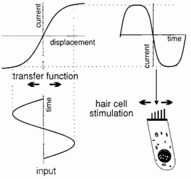

Figure 7. Saturation of current through the hair cells occurs at either displacement direction. To one side the current shuts off completely, to the other it reaches a maximum. Since these cells control the positive feedback, the feedback gain is reduced at higher stimulus intensities.

The filtering and the required amplification is provided by specialised receptor cells that provide positive mechanical feedback at precisely the right position in the cochlea. This amplifies, in a frequency-selective way, the travelling wave on the basilar membrane. Finally, because this amplification is provided by cells which are very similar to the sensory cells themselves, it too is subject to saturation at higher intensities. Thus, variable amplification is provided which compressing the stimulus to the sensory cells into the relatively narrow range of their best sensitivity.

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Hair Cells – Mechanosensors And Motors

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Abstract: Hair cells are the mechanosensors in the cochlea. They detect acoustic vibrations as a result of deflection of the hairs, or stereocilia, on their surface. In addition, hair cells are bidirectional transducers, and return energy to the mechanical system. The bidirectional transduction is responsible for the high sensitivity, high degree of frequency selectivity, and extended frequency range typical of mammalian hearing.

1. INTRODUCTION

The mechanosensory hair cells of the ear are conceptually simple: each has a cell body with a bundle of hairs, or stereocilia, projecting from its top surface (Fig. 1). Sound-induced vibrations produce a bending movement of the stereocilia (see article by Graeme Yates, this issue [1]). When the bundle is deflected, a shearing movement develops between the rows of stereocilia in the bundle. This opens mechanosensitive channels in the stereociliar membrane, so that the electrochemical gradient across the membrane drives ions into the cell. The resulting potential change in the cell can have two effects. It can release chemical neurotransmitter to activate the nerves connected to the hair cell. It can also change the conformation of charged proteins within the cell membrane in the lower (non-stereocilia-bearing) wall of the hair cell, producing a movement of the cell as a whole. This movement is thought to feed back into the mechanical vibrations, to increase the sensitivity of the cochlea to acoustic stimulation.

2. HAIR CELL MECHANOTRANSDUCTION

2.1 The organization of hair cells

Figure 1 shows some of the variations on hair-bundle shape seen in different mechanotransducing organs – from the square bundle found in the chick cochlea, to the straight line bundle of inner hair cells of the mammalian cochlea, and the V-shaped rows of outer hair cells of the mammalian cochlea. However, all bundles are built on the same basic plan, shown in Figure 2. The stereociliar rootlets are hexagonally packed, with the whole bundle being bilaterally symmetric. Specialised links, called tip links, emerge from the tip of each shorter stereocilium on the bundle, to join the side-wall of the adjacent taller stereocilium. Tip links run only in a plane parallel to the axis of symmetry of the bundle. The stereocilia are also joined by other links, just below the tips, which serve to ensure that the stereocilia on the bundle are held together during deflections of the bundle.

2.2 The electrophysiological analysis of mechanotransduction

The clearest analyses of mechanotransduction have come from experiments in which individual hair bundles have been deflected by a fine piezoelectric-driven probe attached to the bundle. These experiments were originally performed by Hudspeth and Corey [2] in hair cells of the bullfrog vestibular system, although they have since been repeated in many other types of hair cell. When a mechanical stimulus is applied to the bundle, individual stereocilia under video-enhanced microscopy are seen to be rigid, pivoting at their rootlets, while the whole bundle stays together, moving as a unit. Measurements of transmembrane currents with an intracellular microelectrode show that membrane channels

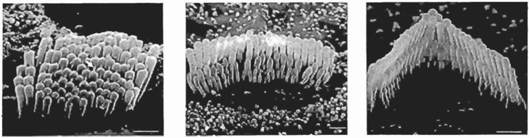
(A) (B) (C)

Figure 1. Hair cells of different conformation as seen in (A) the chicken cochlea, (B) an inner hair cell of the guinea pig cochlea, and (C) an outer hair cell of the guinea pig cochlea. In each micrograph, the body of the hair cell fills the width of the micrograph, and each cell has between 80 and 100 stereocilia. The stereocilia are graded in height across the bundle. The arrow points to a tip link. Scale bars: 1 μm. From [13], Fig. 1A and [16], Figs 3.4 B and C.

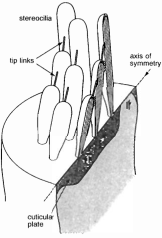

Figure 2. Basic plan of the hair bundle. The stereocilia are graded in height in the direction of the cell's axis of bilateral symmetry. The tip links lie in the vertical plane parallel to this axis. Modified from [17], Fig. 1.

open when the stereociliar bundle is deflected in the direction of the tallest stereocilia, with the direction of greatest sensitivity being along the axis of bilateral symmetry of the cell. The channels are open 5-15% when the bundle is at rest, and they shut completely when the bundle is deflected in the direction of the shortest stereocilia. There is no response to deflection at right angles to the axis of bilateral symmetry.

What is known about the nature of the channels? As in other biological systems, we expect the membrane conductance to be associated with the opening and closing of discrete membrane channels. Measurements of individual channels show that mechanotransduction is indeed subserved by the opening and closing of discrete channels on the stereocilia, with a unit conductance of about 100 pS [3] (Fig. 3A). From the total conductance change during maximal stimulation, it is possible to calculate the number of channels on a hair cell. While there is considerable variation in the numbers over different hair cell types, the numbers are in the range of 40-160 per cell, or about one channel per stereocilium. This is a dramatic result, because it means that all our auditory perception depends on only 6×10^5 transducer molecules.

Individual channels open and close in a stochastic manner, presumably under the influence of thermal energy, with the relative probability of the open and closed states depending on the deflection of the stereocilia (Fig. 3B). The probability is graded with the deflection, such that the probability of an open state increases as a function of the deflection applied to the stereocilia. The large number of channels and the stochastic nature of the opening means that the mechanotransducer currents sum to produce a current through the cell that, though noisy in a way that reflects individual channel opening, is monotonically graded with stereociliar deflection (Fig. 3C). The advantage of stochastic channel opening is that there need be no ultimate lower threshold of hearing: the mean movement at the absolute threshold can be lower than the thresholds of the individual channels, with the absolute threshold depending on the amount of averaging that the central nervous system is able to employ. Comparison of animals' absolute thresholds with measurements of cochlear vibration suggest that at the psychoacoustic detection threshold, the stereocilia are deflected by 0.4 nm, while the movement transmitted to the channel is only 0.04 nm [4]. This is less than the 4 nm calculated for the swing of each channel as it opens and closes [5]. The extraordinary sensitivity of hearing is a reflection of both the molecular scale of channel opening, and the averaging possible in the nervous system.

The currently accepted model of channel activation was put forward by Pickles and colleagues [6]. It was suggested that deflection of the stereocilia would stretch the tip links, directly pulling open the mechanotransducer channels. There are several lines of evidence in favour of this. For instance, the tip links run only along the axis of bilateral symmetry of the cell, which is in turn the direction of mechanosensitivity of the hair bundle. The formulation also explains why deflection of the bundle in the direction of the tallest stereocilia opens the channels, while deflection in the opposite direction closes them. A direct test has recently been conducted by Assad et al. [7]. Removing Ca^{2+} from around the hair bundle selectively cut the tip links, as shown by electron microscopy, and abolished mechanotransduction permanently, without any other apparent changes in the bundle. The bundle also moved in the direction of the taller stereocilia, consistent with a resting tension being taken off the tip links.

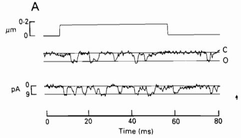

Figure 3. A. The current through a single mechanotransducer channel recorded in a hair cell. The current through the cell membrane moves between two values as the channel opens (O) and closes (C) under the influence of thermal energy. An excitatory deflection was applied during the upwards excursion of the top trace; this increased the probability that the channel would be in the open state. From [3], Fig. 12.

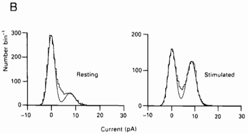

Figure 3. B. Histogram of current distributions for the cell in part A, in the resting and stimulated states. This histogram indicates the relative probability of currents for one particular amplitude of stimulation. From [3], Fig. 14.

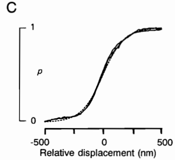

Figure 3. C. Mechanotransducer current as a function of stereociliar displacement for a hair cell of the bullfrog sacculus. The solid lines show the values as a bundle was taken in the inhibitory-excitatory direction and back again. The dotted line shows the theoretical curve derived from the Boltzmann distribution. From [18], Fig. 12.

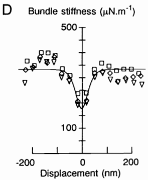

Figure 3. D. Bundle stiffness shows a dip at the centre of the input-output function. This was the point at which the input-output function (Fig. 3C) was at its steepest. From [5], Fig. 4.

Our understanding of the biophysics of channel activation is derived from a kinetic model put forward by Corey and Hudspeth [8], in which it was suggested that each channel was opened by a conceptual entity called the "gating spring", now identified with the tip link. As each channel opened and closed under the influence of thermal energy, there would be a compensatory shortening and lengthening of the link to which the channel was attached. If the link acted as a linear spring and the channel had two possible energy states (open and closed), the Boltzmann distribution predicts that the relation between transmembrane current and stretch applied to the system would be a symmetric sigmoid, as in Fig. 3C. In some other hair cell systems asymmetric sigmoids have also been measured; these could be accommodated by a model in which the channel had two closed states and one open one.

The model requires that the tip link pull directly on the channel; the existence of such a mechanism is supported by a latency in channel opening of only 13 μs (at 37°C). This value was measured in hair cells of the bullfrog vestibular system, a system not likely to be adapted to high-frequency operation [9]. Even shorter latencies are required to subserve the high upper limits of hearing (up to 200 kHz in some marine mammals). All such latencies are however far too short for channel opening to be driven indirectly by biochemical changes in the cell, as are channels in many other biological systems. A second line of evidence that the link pulls directly on the channel has come from studies of changes in stiffness during channel opening. As each channel swings between its open and closed state, the associated movement is coupled back to the stereociliar bundle via the tip link. The movement produces a decrease in the stiffness of the hair bundle as a whole (Fig. 3D); this reduction is greatest half-way up the sigmoidal input-output function (Fig. 3C), the point at which channels have their highest probability of moving between their open and closed states [5].

Do we have any information on the actual sites and nature of the mechanotransducer channels? Electrophysiological measurements of hair cells in situ in the sensory organ show that the channel opening must be in the part of the cell that contains the stereocilia. A number of different experiments, involving the localised detection of current flows or the local application of channel-blocking drugs, have suggested that mechanotransducer current flows into the cell near the tips of the stereocilia, i.e. in the region of the tip links [10-12]. Further localisation depends on theoretical assumptions: because channel opening produces a drop in membrane resistance, we presume that the channels are near the site where the mechanical movements are coupled to the membrane of the stereocilia. The attachment points at either end of the tip link are the most likely sites, although at the moment, we do not know which end. However the fine anatomy suggests that the lower end of the tip link is the more appropriate, because under electron microscopy tension on the tip link appears to distort the cell membrane at this end of the link but not the other one [13]. The race is now on to obtain the molecular structure of the channel. The standard way would be to analyse the genetic material of the hair cells, probing for gene sequences similar to those of other known channels. However, a difficulty is that hair-cell mechanotransducer channels do not appear to have sequence similarity to any other known membrane channel.

3. REVERSE TRANSDUCTION: HAIR CELLS AS MOTORS

As described in the accompanying article by Yates, the mechanically active feedback from outer hair cells is essential for the high sensitivity and high frequency selectivity of mammalian hearing [1]. The mechanism of this mechanical activation is controversial; opinion is now settling to the view that it arises from length changes in the outer hair cells, driven by conformational changes in the cell membrane. As shown by Holley and Ashmore, it is possible to disrupt everything in outer hair cells except the membrane, and still get the length change [14]. The outer hair cell membrane has a unique structure, with a large number of protein particles in the membrane overlying a set of filaments that are wound spirally round the cylindrical cell body [15]. The protein particles are thought to be electrically polarised and geometrically anisotropic (Fig. 4). Stimulus-driven voltage changes across the membrane will tend to realign the molecules, while their close packing and anisotropy mean that the cell membrane will tend to change area. The areal change will be constrained by the spiral filaments to produce a change in length of the cell. The

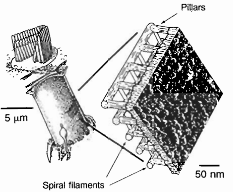

Figure 4. The structures thought to mediate the motility of mammalian outer hair cells consist of particles in the cell membrane, connected by pillars to a series of filaments which spiral around the outer hair cell body. For this diagram, a portion of an actual micrograph of the membrane particles is superimposed on a drawing of an outer hair cell. Adapted from [15], Fig. 5 and [19], Fig. 264.

advantage of this motility is that it would be fast, because it depends on simple biophysical mechanisms rather than slower biochemical ones, essential if the mechanical amplification is to work in the upper reaches of many mammals' audio ranges. However, there are a number of points still unclear: (i) the RC cutoff frequency of the outer hair cell membranes is around 1 kHz; it is not therefore clear how voltage changes across the cell membrane can be sufficient to drive the molecular realignment at the high frequencies (e.g. 10 kHz and above) at which amplification can occur. One possible solution to this is that the currents across the cell membrane, that have hitherto been interpreted as flowing through the capacitance of the cell membrane, are in fact carried by charge movement during the molecular realignment. However, this would require revision of hair cell measurements in this frequency region, because at high frequencies the transmembrane current has been thought of as capacitive. (ii) It is not yet decided how the length change of an outer hair cell could feed back to produce a vibration of the organ of Corti as a whole, and so amplify the mechanical travelling wave on the basilar membrane.

4. CONCLUSION

Hair cells are adapted to obtaining a low threshold in the face of thermal noise. By having many channels on a hair cell, each in thermal equilibrium with an elastic activating link, it is possible to average the transducer currents of individual channels. This produces a mechanical threshold which is below the magnitude of the dimensional change required to open and close any one channel. In addition, the active mechanical feedback from hair cells not only magnifies the mechanical stimulus to the hair cell, but, by introducing active amplification, is able both to increase the frequency selectivity of cochlear analysis and to reduce the bandwidth of thermal noise coupled to the hair cell.

ACKNOWLEDGMENTS

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The Ear as an Acoustical Generator: Otoacoustic emissions and their diagnostic potential

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Abstract: When sound enters the cochlea it evokes an electromotile response of the outer hair cells which is present in normal ears but absent in mild sensorineural hearing loss. This activity modifies the mechanical motion of the basilar membrane nonlinearly if the stimulus frequency is close to the characteristic frequency of each place. A bi-product of this motor activity is a reverse travelling wave which may be detected as a sound in the ear canal with a sensitive microphone. Such sounds may be spontaneous or may be evoked by specific test stimuli such as clicks or pure tones. Analysis of these emissions provides a map of damage to the ear which apparently may be extensive before any sign of hearing loss occurs. The difference between estimated age and chronological age for any ear may provide early warning of increased susceptibility to hearing loss which may be useful in the prevention of hearing loss. Time-frequency distributions may offer an approach to the dynamic characterisation of specific outer hair cell pathologies to assist in the determination of susceptibility.

1. INTRODUCTION

Otoacoustic emissions (OAEs) were first described in detail by David Kemp (1) as sounds which could be measured by a microphone sealed in the ear canal. Attention was drawn to the phenomenon that certain individuals were known to emit sounds from their ears which could be heard by others; published cases include a dog with a tonal emission at 53 dB SPL. *Spontaneous otoacoustic emissions* (SPOAEs) have since been described extensively (2) and are thought to be associated with punctate lesions along the cochlear partition in cochleas having relatively little damage. Fig. 1 shows an example human SPOAE spectrum. Remarkably SPOAEs are quite common yet people exhibiting them do not hear them except in a tiny fraction of cases. Emissions may also be evoked by sound and their dependence upon stimulus parameters characterised so as to provide a great deal of clinically useful information.

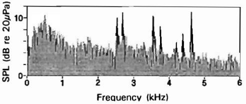

Figure 1. An example of spontaneous emissions from a human ear with components between 2 and 5 kHz.

1.1 Origin of otoacoustic emissions

OAEs are generated by the electromotile response of the outer hair cells (OHC) in the cochlea. This activity produces a reverse propagating travelling wave which reaches the middle ear after a delay related to the site of evoked activity. This activity has been classified according to the three purported generation mechanisms. The first is an electro-kinetic response of the specialised cell membrane, akin to piezoelectric action (3); the second form uses the triggered chemical reaction between actin and myosin molecules such as occurs in muscle (4) and the third form involves cell length changes due to changes in cell volume (5). A high frequency form of motility such as the first is necessary to explain features of mechanical behaviour such as emissions due to nonlinear intermodulation distortion between high frequency primary tones. The latter two "slow" forms are necessary to account for adaptive-type behaviour seen as movements in the baseline position of the basilar and tectorial membranes due to sound (6) and electric stimulation (7). OHC motor responses *in vivo* may be modulated by the medial efferent nerve fibres emanating from the contralateral ear (2,8).

1.2 Evoked OAE measurement of ear performance

The object of each of the methods of evoking OAEs is to scan along the 32 mm length of basilar membrane for tuned OHC motor response so as to produce a tonotopic "map" of the activity. The microphone probe assembly, sealed in the earcanal (Fig. 2A), measures both the evoking stimuli and the evoked OAE (EOAE) response. It is necessary to be able to separate sounds specifically due to the evoked OHC activity from other sources: (i) the stimulus produced by the sound source, (ii) passive echoes from the external and middle ear cavities (Fig. 2A) as well as (iii) background noise of both external and internal origin. Elimination of the first two is achieved by capitalising on the fact that the active response depends nonlinearly upon stimulus strength due to the biological characteristics of the hair cells. Passive components of the response can be

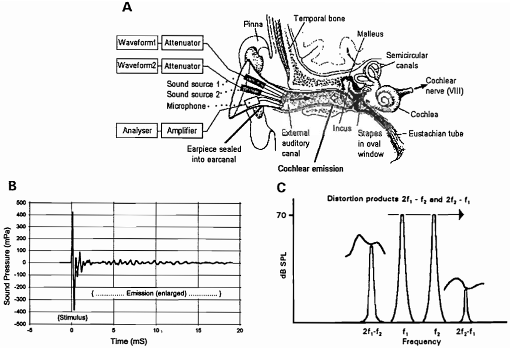

Figure 2. Panel A shows the general arrangement for evoked otoacoustic emission measurements with the microphone recording both the stimulus and the response. Two miniature electret microphones may be connected differentially so that common mode (mostly external) noise will be reduced. Panels B and C respectively show microphone responses for the TEOAE and DPOAE methods, and how the stimulus is separated from the response in time or frequency.

the response can be eliminated by separation in time or frequency and/or subtraction of any linear component. Most internal noise will be due to asynchronous OHC activity such as the unstable activity which give rise to spontaneous emissions, so recording the noise signal in the absence of the stimulus is important.

1.2.1 Transient evoked otoacoustic emissions (TEOAEs) are generated by clicks or tone bursts and may be separated from the stimulus in time (Fig 2B) like an echo from its source. Scanning occurs because the signal generates a travelling wave-front which propagates from the base to the apex evoking OHC activity as it progresses. Activity from the base of the cochlea is evoked by high frequency components and appears in the emission after short delays. Activity from the apex of the cochlea appears with longer latency (*ca.* 10 ms). The spectrum of click-evoked emissions is obtained by Fast Fourier transformation (FFT) after removing the relatively large stimulus transient (Fig 2B). External noise can be handled with artifact detection and removal techniques as well as signal averaging time-locked to the stimulus click presented typically some 1000 times.

1.2.2 Distortion product otoacoustic emissions (DPOAEs) For continuous stimuli such as pure tones or pairs of pure tones the response tone must be separated either in frequency or in phase. The nonlinear response is plotted as the magnitude of the cubic distortion product mf_1-nf_2 (2) for integers m and n as the frequency range is scanned (Fig. 2c) with a lock-in amplifier or spectrum analyser. This mostly occurs in discrete steps of primary tones f_1 and f_2. The $2f_1$-f_2 response gives best sensitivity with primaries at a fixed separation of about 0.3 octave. Response values are often plotted versus the geometric mean of the primary frequencies reflecting the expected site of origin in between the places for the primary tones.

For either of these two most popular methods, any frequency with a high level response is taken to indicate viable motor activity at the appropriate tonotopic location. Conversely, notches in the response spectrum are believed to indicate sites of inferred damage, so that the spectrum gives an approximate map of damage to the ear. The click-evoked method is slightly faster than the distortion product method, but the latter may scan any limited frequency range with arbitrary resolution. Adult OAE screening takes about 4 minutes per person compared to typically 15 minutes for pure tone audiometry (PTA) (9). Recently Thornton (10) has reported that using maximum length sequences, the data collection time may be reduced to a few seconds.

1.3 Audiometric testing of ear performance.

An audiogram is a subjective response measure of ear sensitivity (dB HL) to pure tones at standard frequencies 0.125, 0.25, 0.5, 1, 2, 4, 6, 8 kHz. It has long been known that PTA, while providing a measure of the best sensitivity

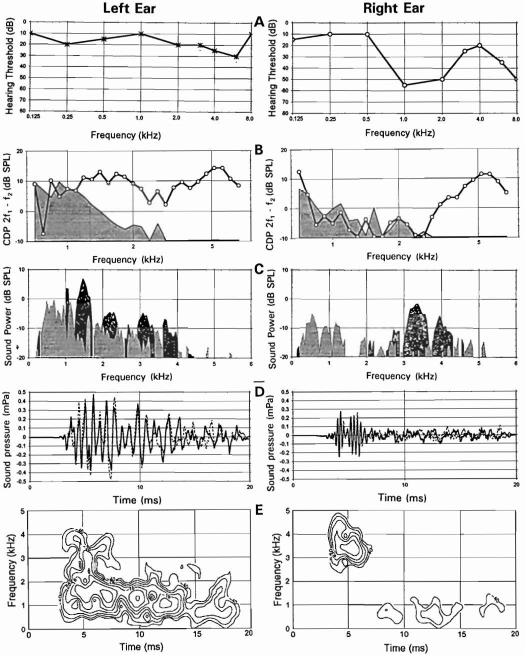

Figure 3. Subjective and objective measures of left and right ears of one subject: Panels A, pure tone audiogram (dB hearing level); Panels B, frequency dependence of the cubic distortion tone $2f_1 - f_2$ (dB SPL) and background noise (grey area); Panels C, cross power spectrum (black area) of the pair of time traces for each ear in panels D, and noise spectrum (grey); Panels D, waveform pairs after total of 1 minute averaging 1040 click responses (stimulus artifact removed); Panels E, Equi-SPL time-frequency contours, 6dB steps. Each 512 point waveform in D is broken into 64 overlapping frames using a sliding Hanning window. Each frame 64 points in length and overlaps its predecessor by 56 points. Each frame is padded with 64 zeros then each resulting frame is FFTed (order 7) and contours derived.

of the ear to a pure tone, is not a particularly sensitive measure to overall ear performance; speech discrimination may deteriorate and tinnitus (phantom sounds generated internally) can arise without any change in threshold from normal. Also in cases of hearing loss pure tone hearing levels are a poor measure of actual hearing disability. For example, people with the same audiometric pattern of hearing loss may have quite different levels of difficulty in comprehending speech.

2 COMPARISON OF SUBJECTIVE AND OBJECTIVE METHODS

Pure tone audiometry is slow because of the need to search for a fixed response, viz.: threshold and because the subject must make decisions in a task which may be difficult. It may be unreliable because each subject may adopt different criteria for certainty. OAEs on the other hand, being objective, may obtain a family of frequency response characteristics for steps in stimulus level. Also the emission level may be quantified as a function of stimulus level for fixed frequency. Hence reasons to compare subjective and objective methods include: (i) speed advantage, (ii) frequency resolution of microstructural damage, (iii) differential sensitivity to ear damage, (iv) applications such as screening for ear damage in infants or people who cannot (or will not) provide an accurate assessment by conventional means, (v) differentiation between cochlear- and retrocochlear- abnormalities, (vi) potential early warning of hearing loss.

Figure 3 shows a comparison of various behavioural and objective results from the left and right ears of one subject. The pure tone audiograms in panels A reveal normal hearing in the left ear while the right ear exhibits a hearing notch from 0.5 to 2.5 kHz due to acute noise trauma many years previously. The shape of the $2f_1$-f_2 "DP-gram" in panels B above the noise level (grey area), obtained using the Otodynamics ILO88/92 system, reflects the general shape of the audiogram quite well yet has not required any patient response other than general co-operation. Panels D show the windowed click-evoked emissions obtained with the same system. Each panel contains a pair of traces because it has been found that the cross-power spectral estimates between the two traces give the best spectral estimates of the OHC activity (panels C). Panels E show time-frequency contours computed from the records in panels D using the short-time Fourier transform (11) indicating the availability of a wealth of information about dynamic ear performance. Since "slow" motility (see Sect. 1.1) is normally evoked from the entire length of the cochlea, it also appears with short delays as well so that the site of low frequency activity is less specific (Panel E, left). The high-frequency response of the TEOAE is more limited than the DPOAE, probably because short latency high frequency responses are removed with the artifact.

Neonatal screening for hearing impairment carried out shortly after birth (2), is currently the primary application of the technique. It constitutes a breakthough for identification of potential learning problems in young children because (i) the test is objective and noninvasive, (ii) the emission levels are normally high, (iii) very high values for sensitivity and specificity are possible and (iv) alternative forms may be too slow, expensive or impractical for mass screening. DPOAEs are particularly valuable for comparing with contours of audiograms. In general, if emissions exist at any frequency at which more than a mild hearing loss is registered, the threshold might usefully be re-checked. In the same category of emissions but no hearing, it is likewise possible to differentiate between cochlear damage and hearing loss of more central origin, such as tumours of the auditory (VIIIth) nerve.

TEOAEs more rapidly provide higher spectral resolution than either the pure tone audiogram or the DP-gram which for speed are limited to about 2 and 12 points per octave respectively. While the ears of neonates show spectra which are continuous, perhaps with some ripple; the spectral "drop-outs" deepen and widen with increasing age (9,13). Our otoacoustic emission database of over 3000 TEOAE records has many cases of apparently prematurely aged ears where the low emission strength is due to fragmentation of emission spectra -- we have dubbed this the "picket fence effect". It is characteristic of individuals who have been working in noisy occupations for many years. Moreover, very fine fragmentation approaching line spectra has very frequently been observed in longtime members of the music industry and young persons who have had significant loud music exposure, a feature which would not so readily have been detected with DPOAEs.

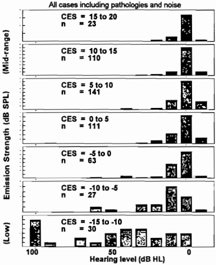

*Figure 4. Comparison of coherent emission strength (CES dB SPL, 1-4 kHz) with pure tone thresholds (1,2 and 4 kHz) for 503 ears for numbers **n** in each CES range shown. Neonatal values range to 38 dB SPL. Hearing levels remain normal while CES is positive.*

To arrive at a single figure descriptor of damage to any ear we have computed *coherent emission strength* (*CES* dB SPL), or that fraction of the total emission which is due specifically to stimulus-locked activity (9). Infant CES values can range up to 38 dB SPL in response to 80 dB peak clicks. The CES values were plotted against the PTA thresholds (both from 1 to 4 kHz). Hearing levels remain within normal limits while the CES values are positive (Fig. 4). This means that CES maydecrease by about 80 percent of its range before a mild hearing is expected. On this scale, individuals with high values of CES are less susceptibile to acquiring a mild hearing loss than those with low values. Indeed, for any age the predicted percentages of the Australian population affected with hearing loss agree with actual percentages shown in the 1989 British epidemiological survey (14).

3 COCHLEAR MECHANICAL LOSS

It is an axiom of audiology that normal hearing levels indicate no impairment. Yet one of the major unexplained features of hearing impairment is its subtlety of onset -- the person affected can remain unaware of the problem for years, common with the insidious nature of many other aspects of human aging. Because of the differential sensitivity of OAEs and PTA to quantify cochlear damage shown in Fig. 4, the pure tone audiogram may not be a direct measure of cochlear damage so much as a measure of how much the cochlea can maintain normal performance despite ongoing damage. Recent studies comparing structure and function in the cochlea have shown that there is considerable redundancy in the numbers of OHC (see 9). At birth each ear has about 12000, many more than we apparently need to maintain normal hearing sensitivity. In mammals lost cells are not replaced so it seems a reasonable hypothesis that the emission strength (CES values) give a reasonable net measure of total numbers of remaining OHCs. Certainly Fig. 4 describes a popul-ation large enough for individual variable factors such as sound transmission through the middle ear to have washed out of the overall trend. So why should loss of OHC not immediately lead to hearing loss? According to a recent model (13), the ear possesses an inherent property of re-mapping frequency-to-place so as to avoid gaps in frequency detection at low levels because of scattered OHC loss. So, hearing loss only occurs once the limits of re-mapping are exceeded.

The concept of cochlear mechanical loss highlights the potential for OAEs in future clinical practice. It is likely that many incidences of sudden awareness of hearing loss in future will be recognised to be due to just a small but critical degree of damage which is additional to the damage accumulated over the lifetime of the person. Noise is not the only cause of accumulated damage. There is whole range of conditions adverse to cochlear function: acute anoxia at birth, high blood pressure, head trauma, the effects of ototoxic drugs including some aminoglycoside antibiotics such as streptomycin, and gentamycin which is commonly given prophylactically to guard against infection in premature babies, or certain diuretics particularly combined with antibiotics. In the future OAEs may provide a more accurate assessment of accumulated damage or that sustained in the workplace. Once individual aging characteristics and dynamic EOAE characteristics are defined, testing baseline audiometry may usefully be supplemented with relatively inexpensive baseline measures of cochlear mechanical damage.

4 DEFINING SUSCEPTIBILITY IN TERMS OF EFFECTIVE EAR AGE

The reason why some people are highly susceptible to hearing loss, while others can grow old without developing any hearing loss may now be explained. In a pilot study of the Australian population estimated minimum and maximum rates of aging are CES<4dB/decade and >8dB/decade (12). Research is currently aimed at comparing the estimated effective age of any ear with its chronological age (e.g. 60 vs 28 in the case of a percussionist). Given the ear age plus current rate of decline in CES, the number of decades of normal hearing remaining can be estimated. EOAEs therefore offer great potential for the prevention of hearing loss through mass screening for ear damage.

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The University of Melbourne/Nucleus Multiple-Channel Cochlear Implant

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Abstract: The history of the development of the multiple-channel cochlear implant by a research team at the University of Melbourne, in collaboration with Nucleus Ltd, is reviewed and related to various strategies for speech processing and cochlear stimulation for the profoundly deaf. The results of clinical trials are summarised and evaluated.

REVIEW

In the 1960s the fundamental question was: could direct electrical stimulation of auditory nerve fibres help profoundly-totally deaf people understand connected or running speech? Profoundly-totally deaf people have very little residual hearing due to loss of the organ of Corti, and could therefore not be assisted by amplifying speech sounds with a powerful hearing aid.

As frequency information was known to be important in recognizing phonemes and words it was considered necessary to see how well electrical stimulation could reproduce the coding of frequency. Frequency was thought to be coded by spatial and/or temporal mechanisms. Spatially this was through the place or site of stimulation of the auditory centres. Temporally it was through the rate of nerve firing or more correctly the time intervals between nerve action potentials.

Studies specifically designed to investigate these questions on anaesthetized experimental animals showed that electrical stimulation could not reproduce the sustained firing seen with acoustic responses at rates above 200-500 pulses/s. The probability of the neurons firing at each pulse interval was greater for electrical stimulation than for sound (Clark, 1969). Furthermore, it was demonstrated that periodic electrical stimuli were encoded in the discharge of neurons up to a rate of 400-600 pulses/s (Merzenich et al., 1973). As the data from the above initial study (Clark, 1969) had been obtained from the auditory pathways in the anaesthetized animal, it could not be concluded the findings were necessarily applicable to the coding of frequency in the intact alert animal. To help resolve this matter a series of behavioural studies was undertaken on the experimental animal (Clark et al., 1972; Clark et al., 1973). These showed the animals had severe limitations discriminating different rates of stimulation above 200-600 pulses/s.

As our initial research on acute preparations and behavioural animals showed the limitations of using electrical stimulation to code frequencies above 500 pulses/s on a temporal or rate coding basis, it was considered that a single-channel implant would not be satisfactory for conveying important speech frequencies above 500Hz. It was necessary to convey frequencies up to approximately 4000Hz for adequate speech comprehension. For this reason, in 1971-72, we embarked on the development of a fully-implantable, multiple-channel (multiple-electrode) cochlear implant that would thus enable us to code frequencies above 500Hz (essential for speech intelligibility) on a place coding basis.

It was considered that the device needed to be fully-implantable, as a plug and socket could result in infection extending from the site where the socket emerged through the skin to the tissues within the body. This meant we had to design the electronic circuitry of the implantable receiver-stimulator unit so that a number of possible speech processing strategies could be evaluated on our patients. A fully-implantable system would not be as "transparent" as a plug and socket.

Having embarked on the development of a multiple-channel implant it was also necessary to study how best to site the electrodes within the cochlea and provide appropriate electrical stimuli, to both minimize trauma to the neurons we hoped to stimulate as well as localize the electrical current to discrete groups of nerve fibres for place coding. This involved computer modelling and animal experimental studies (Black and Clark, 1977; Black and Clark, 1978; Clark, 1973; Clark et al., 1975). The possibility of localizing the current to discrete groups of nerve fibres by using bipolar stimulation was demonstrated by Merzenich (1974).

Our first cochlear implant operation on a postlinguistically deaf adult with a profound-total hearing loss was carried out on 1 August 1978 (see Figure 1). Postoperatively we undertook psychophysical studies to explore his percepts for variations in place, rate and intensity of stimulation. They confirmed the limitations of discriminating rate of stimulation above 200-300 pulses/s seen previously with our studies on experimental animals. They showed that place pitch was different from rate pitch. It had timbre which varied from sharp to dull depending on whether a basal (high frequency) or apical (low frequency) electrode was stimulated respectively. The patient could also scale place pitch well for site of stimulation indicating that the current spread for common ground stimulation with our banded electrodes provided satisfactory current localization. Common ground stimulation, available with the prototype implant, resulted in current flowing from an active electrode to all the other

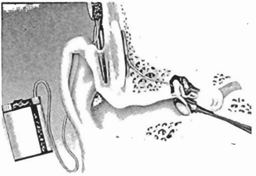

Figure 1. A diagram of the Nucleus implantable receiver-stimulator and wearable speech processor unit for clinical trial by the FDA illustrating the components. Speech is picked up by the directional microphone and electrical signals sent to the speech processor for coding. The coded signals and power to operate the implant are transmitted through the intact skin by radio waves (inductive coupling). The implant decodes the signals and directs them to the electrodes in the array lying around the basal turn of the inner ear.

electrodes on the array connected together electronically. Finally, studies on loudness showed this varied primarily with stimulus current level and the loudness growth due to increase in current was much steeper than for acoustical stimulation in normal hearing subjects.

Our first speech research involved presenting speech through a processor which modelled basilar membrane motion and the fine timing of auditory nerve firing. We did this in the belief that in spite of the limitations on the discrimination of rate of stimulation the closer we could get to simulating the spatio-temporal patterns of auditory nerve firing with speech sounds the more chance we would have of the patient understanding running speech. However, this strategy did not provide significant help, and this was thought to be due in part to unpredictable variations in loudness from summation of electrical fields with simultaneous stimulation on neighbouring electrodes.

The most important clue in developing a speech processing strategy to help our patient understand running speech came when he was asked to mimic the sounds he experienced when different single electrode sites were stimulated. He imitated the percepts as vowels and the vowel varied according to the place of stimulation. In explaining this relationship and in developing an appropriate speech coding strategy for multiple-electrode stimulation we considered it important to determine what equivalent acoustical signals could produce the spectral colours (/ɒ/, /ɔ/, /ɛ/, /ɪ/, /i/) or (/hot/, /cord/, /head/, /hit/, /seat/) perceived by the patient (Tong et al., 1979). We were helped in this regard by a study by Delattre et al., (1952) who had shown that single-formant synthetic vowels with formant frequencies at 720Hz, 2160Hz and 3000Hz were identified respectively as having vowel colours corresponding to /ɔ/, /ɛ/, /ɪ/. This suggested that the spectral colours produced by electrical stimulation on single electrodes could be approximately equivalent to those produced by acoustical signals with their spectral emphases centred at frequencies ranging from 720Hz to above 3000Hz. Research on our patient also showed that we could shift the vowel perceived from /ɔ/ to an /a/ or /cart/ by increasing the current level and we attributed this to a shift in the population of neurons stimulated and an averaging process referred to by Plomp (1976) for spectral components of acoustic stimuli.

We also carried out psychophysical studies using two electrodes stimulated simultaneously and at the same rate. The vowel perceived was different from that for each one stimulated separately. When we stimulated one electrode resulting in /ɒ/ and combined this with another resulting in /ɪ/ the percept was/ʌ/or /hut . This suggested that an averaging process was taking place in the brain when the two populations of neurons were excited for spectral components in the two vowels. Another important finding was that when two nearby electrodes were stimulated simultaneously with rates which differed by approximately 5%-7% the patient perceived a consonant and following vowel. With the electrodes used this was /də/ or /dirt/. Data from the study suggested that beating was occurring, and that amplitude changes from the stimuli moving in and out of phase were responsible for the perception of the consonant in conjunction with the vowel. The stimuli were representing some of the acoustic cues for the coarticulation of consonants and vowels (Tong et al., 1979).

In deciding how to implement a speech processing strategy we considered we should extract one formant frequency initially, and code this as place of stimulation. We had seen that single electrode stimulation could produce vowel colours that were equivalent to those for the single formant representation of vowels. The relationship between a single formant representation of the first and second formants in vowels was, however, complex and not well understood. For that reason it was more appropriate to extract the second formant frequency as it had been shown from research by Potter et al., (1947), Cooper et al., (1952), Liberman et al., (1954), Fant (1956) and others to be the formant providing most speech information. It was coded as place of stimulation because it was in a high frequency range and our initial psychophysical studies on the patient had shown that high frequencies could be coded as place pitch.

The decision to extract the second formant frequency was a change in the direction of our research. It meant preprocessing of speech information, selecting important cues and determining how best to present the information to the nervous system. If electrical stimulation of the nervous system produced an information "bottleneck" as indicated by our animal experimental and human psychophysical data, it was important to be selective with the information presented through the "bottleneck". As a result of this decision we also extracted the fundamental or voicing frequency as it is not visible on the lips and its presentation would therefore be a great help as a lipreading aid. Voicing which is low in frequency was appropriately coded on a rate or temporal basis because our previous experimental animal and human psychophysical findings had shown that frequencies up to 300-500Hz could be coded this way.

In addition, it was considered important to present the coded fundamental frequency only to the individual electrodes presenting second formants on a place coding basis. This would ensure that the unpredictable variations in loudness that occurred with summation of electrical fields from simultaneous stimulation on two or more neighbouring electrodes with the physiologically-based processor would not occur. Finally, the intensity of the second formant was coded as current level on each electrode used to code second formant frequencies.

This inaugural formant or cue extraction speech processing strategy was first implemented on a laboratory-based computer in 1978, and shown to provide the patient with approximately a 400% improvement in understanding running speech when using electrical stimulation combined with lipreading compared to lipreading alone. He was also able to understand some running speech when using electrical stimulation alone. A second postlinguistically deaf adult who had been profoundly deaf for 13 years rather than two years in the case of the first patient received a multiple-electrode cochlear implant on 13 July 1979. He obtained results that were similar to the first patient suggesting that the coding strategy might be generally applicable. It was also an important finding that even after 13 years of no auditory input he was still able to remember the sounds of speech and this showed his auditory pathways could process the coded speech information. In April 1980 the speech processing strategy was realized as a portable unit with dimensions 15x15x6.5cm and weight of 1.25Kg.

The laboratory-based speech processor consisted of three basic sections: speech signal parameter extraction; encoding of speech parameters to electrical stimulus parameters; and digital configuration of electrical stimulus data. Four speech signal parameters were estimated every 20 ms in the parameter extraction section. The fundamental (voicing) frequency (FO) and a low frequency energy measure (AO) were estimated by measuring the period and the average amplitude of the output waveform of a lowpass filter. The second formant frequency (F2) and its amplitude (A2) were estimated by measuring the zero crossings and average amplitude of the output waveform of a bandpass filter. The speech parameter estimates (FO, AO, F2, A2) were transformed to electrical stimulus parameters every 20 ms in the encoding section. Only one electrode was activated in any 20 ms time frame. For a given F2 estimate an electrode was selected according to a predetermined F2-to-electrode transformation map: the F2 frequency range was divided into nine subbands; each subband was assigned to a particular electrode. The subband of lowest frequency was assigned to the electrode with the dullest sensation, while the subband of highest frequency was assigned to the electrode with the sharpest sensation. The current level for the single-electrode pulse train was determined from A2. A 20 ms speech segment was classified as voiced if AO exceeded a pre-selected threshold, and unvoiced otherwise. For unvoiced speech segments, a constant low pulse rate for electrical stimulation was used. This low rate was used as it produced a sensation described as 'rough' which is the closest response to that of noise perceived by normal hearing subjects. For voiced speech segments, the pulse rate was proportional to FO, and was higher than the pulse rate used for the unvoiced segments. Given the electrode selection, current level and pulse rate for a 20 ms time frame, the digital configuration section of the speech processor formatted the electrical stimulus data, and transferred these data to the external transmitter unit (Tong et al., 1980a). The portable speech processor used the same overall coding strategies as the laboratory-based speech processor but analyzed speech every 10 ms rather than 20 ms.

Establishing the benefits of the inaugural FO/F2 speech processing strategy required setting up a series of speech perception tests in standardized conditions. This involved making sure that the test material was prerecorded, not previously presented, and administered in controlled conditions. To show the benefits of the implant in understanding running speech not only did we use the phonetically-balanced AB word test (Clark et al., 1981a) but also the CID everyday sentence test (Clark et al., 1981b) and then later the Tracking test (Martin et al., 1981). The testing was also carried out for electrical stimulation alone, lipreading alone and electrical stimulation combined with lipreading.

The results of the initial testing are reported in more detail elsewhere (Clark et al., 1981 a, b; Martin et al., 1981). In summary, however, with AB words the first patient obtained a score of 10% for words and 20% for phonemes using electrical stimulation alone, and an improvement for electrical stimulation combined with lipreading compared to lipreading alone of 300% (words) and 38% (phonemes). With CID sentences he obtained a score of 14% for electrical stimulation alone and a 386% improvement for electrical stimulation combined with lipreading versus lipreading alone. Similar results were obtained on the second patient.

Although the inaugural speech processor was very effective in providing help in understanding speech when used as a lipreading aid it was of more limited help when used alone without lipreading. Furthermore, its performance was significantly degraded when the signal-to-noise ratio was reduced. For these reasons we undertook further psychophysical research to help determine how well stimuli of relevance to speech comprehension were perceived. We also analyzed the speech perception results to determine which features were most effectively transmitted.

One important question was whether rate (temporal) or place coding was effective in conveying time varying frequency information which is a feature of speech signals. With speech there is a slowly varying fundamental or voicing frequency and consonants, in particular, have frequencies that change rapidly over a duration of about 20 ms (Clark et al., 1987).

Research to answer this question (Tong et al., 1982) showed that when the place of stimulation was varied across adjacent electrodes the two patients could discriminate the transition well for durations of 25, 50 and 100 ms. On the other hand, when varying pulse rates on a single electrode , there was a marked degradation in performance from 100 to 25 ms. This finding helped establish the validity of our speech processing strategy where variations in place of stimulation for F2 could be discriminated for the short durations of consonants. Nevertheless there was still a need that future research should aim at maximizing the amount of information transmitted on a place coding basis over short durations in time. Furthermore, an interesting sequel was that the research helped show that acoustic frequency discrimination probably takes place on a place coding basis, i.e. when we perceive a change in frequency this occurs through a shift in site of stimulation. With acoustic stimuli it is difficult to separate temporal from place coding, and the relative importance of each was not well established. With electrical stimulation place and temporal coding can be artificially separated, and it provided fundamental information on the coding mechanisms involved in frequency discrimination. Although the research on time varying rate of stimulation showed perceptual limitations for durations of 25 and 50 ms, satisfactory discrimination at 100 ms was sufficient to code the slow variations of the fundamental frequency and confirmed the suitability of the FO/F2 strategy.

A further question of importance was the coding mechanisms for loudness, and in particular the extent to which loudness was a function of repetition rate. Basic physiological studies had shown that to acoustic stimuli the mean firing rate of units increase over a 20-50dB intensity range, and that the population of neurons stimulated also increases. The interrelation between the stimulus rate and excited population is not well understood. For our speech processing strategy it was necessary to know that if we coded the fundamental frequency as rate of stimulation to what extent would variations in rate produce changes in loudness, and could this be controlled if necessary to improve the speech processing strategy. The study was undertaken by comparing loudness changes for stimuli with single pulses per period (SPP), and stimuli with multiple pulses per period (MPP). With the MPP stimuli the mean pulse rate could be kept constant over time while the period of each group of pulses was shortened and the repetition rate increased. The study showed that the MPP stimulus produced approximately equal loudness with variations in repetition rate. The data from the study also indicated that loudness is a function of the physical variables, charge per pulse and overall pulse rate. Loudness did not necessarily increase with charge per unit time (Tong et al., 1983a).

Another question in establishing the effectiveness of our speech processing strategy was the extent to which interaction occurred between repetition rate and place of stimulation. This was relevant as the strategy involved presenting the fundamental frequency as rate and second formant as place of stimulation. Any significant interaction between repetition rate and place of stimulation would lessen the effectiveness of the strategy. The study was undertaken by asking the subject to categorize the stimulus as a "question" or "statement" on the basis of whether there was a rising or falling pitch produced by a slow change in rate of stimulation. The rate trajectories were varied on three separate electrodes from apical, middle and basal sites to see if there was an interaction between rate and place pitch in coding the fundamental frequency of speech. The SPP and MPP modes of stimulation were also compared to help determine whether variations in loudness or pitch changes alone were responsible for making "question" and "statement" judgements. The results firstly showed there was a significant interaction between rate and place pitch for the apical electrode but not so for the electrodes in the middle and basal regions. The interaction for the apical electrode probably occurred because a low stimulus rate occurred at an electrode site in a lower frequency region of the cochlea. The interaction was thought to be of secondary importance for speech perception in cochlear implant patients. Secondly, the results showed the lack of any significant difference between SPP and MPP modes of stimulation. This suggested that rate pitch alone and not variations in intensity were being used in coding changes in fundamental frequency.

As the FO/F2 speech processing strategy presented the fundamental frequency across electrodes when coding F2, it was important to not only study the interaction between rate and place pitch for individual electrodes, but for varying rate of stimulation across electrodes. The categorization performance for the presentation of the fundamental frequency across electrodes was compared with that on separate electrodes, and no significant difference seen. There was also no difference whether rate was varied across electrodes in an apical to basal or basal to apical direction. Furthermore, the categorization performance for electrical stimulation was similar to that reported by Fourcin et al., (1979) for acoustical stimulation with fundamental frequency trajectories superimposed on the syllables "oh". This correspondence between acoustical and electrical results suggested that the perception of pitch contours for electrical repetition rate in the presence of a variation in electrode position was similar to the perception of pitch contours for fundamental frequency superimposed on a variation in the spectral envelope of an acoustical signal.

Finally, a study was undertaken to confirm that the percepts for rate and place pitch were separate. The study showed that dissimilarites between the two pitch percepts could be best explained in two dimensions of perceptual space. This confirmed both our initial findings that rate and place pitch were different, and the lack of interaction between the fundamental frequency and stimulation on middle and basal electrodes. The finding also helped establish the validity of the FO/F2 speech processing strategy.

Understanding how the FO/F2 processor was effective in helping profoundly deaf people understand running speech and how to improve it, particularly for electrical stimulation alone, required not only the psychophysical studies referred to above but a detailed analysis of speech perception performance. An initial analysis of speech perception showed that vowel recognition for electrical stimulation alone (77% mean score) was better than for consonants (35% mean score) (Tong et al., 1980b). As consonants are more important than vowels for speech intelligibility, improvements in the perception of the former were obviously necessary. For this reason we analyzed the particular features of consonants perceived in a number of studies (Tong et al., 1980a; Clark et al., 1981c; Dowell et al., 1982). The results showed that for voicing, 30% information was transmitted with electrical stimulation alone, 0% with lipreading alone, and 47% with electrical stimulation combined with lipreading. These results confirmed that voicing, which is not visible on the lips, was being effectively transmitted by the FO/F2 speech processing strategy. A similar trend was seen for the nasals (/m/, /n/). On the other hand the reverse applied for affrication (/f/, /v/, /s/, /z/) and place (/b/, /d/, /g/, /p/, /t/, /k/). In the case of affrication the percentage information transmission was 9% with electrical stimulation alone, 58% with lipreading alone and 75% with combined electrical stimulation and lipreading. For place the information transmission was 14% with electrical stimulation alone, 70% with lipreading alone and 74% with electrical stimulation combined with lipreading. These results suggested there was a need for the transmission of more high frequency information for improving the perception of affrication and the transfer of more information over short durations for the phonemes conveying place information.

While the above studies were being undertaken to study how the FO/F2 strategy might be improved, work was carried out with Nucleus Limited to help in the industrial development of the implantable receiver-stimulator and wearable speech processor for clinical trial for the US Food and Drug Administration (FDA). The implantable receiver-stimulator (Clark et al., 1983) was made more robust than the prototype developed by The University of Melbourne, and had the electronic circuit streamlined in the light of findings with the prototype device (Figure 1). The speech processor (Clark et al., 1983) was made smaller (Figure 1), and it implemented the inaugural FO/F2 strategy. We also undertook a series of additional biological studies at this time that were subsequently of value in helping to establish for the FDA that the device was safe as well as effective (Clark et al., 1987).

The FDA clinical trial was carried out initially by centres at The University of Melbourne; University of Iowa; Baylor College of Medicine, Houston; Mason Clinic, Seattle; New York University; Good Samaritan Hospital, Portland; University of Toronto; Louisiana State University, New Orleans; Medizinische Hochschule, Hannover; and the University of Sydney. This wider clinical trial confirmed the initial results obtained by The University of Melbourne. On 40 patients it showed a mean improvement in CID open-set sentence tests from 52% for lipreading alone to 87% for lipreading combined with electrical stimulation three months postoperatively (Dowell et al., 1986). For electrical stimulation alone the mean open-set CID sentence scores on 23 patients were 16% (range 0-58%) three months postoperatively, and 40% (range 0-86%) 12 months postoperatively. This trial also showed that there was considerable variation in patient performance (a finding in all subsequent trials and for all devices to this day), and that significant learning was required to effectively use the speech sounds induced by electrical stimulation.

At the time there was considerable debate as to whether multiple-channel (multiple-electrode) stimulation was really more effective than methods of single-channel stimulation. Reports occurred from different centres which did not take into account patient variation and which used a variety of assessment procedures. For this reason a controlled comparative study was undertaken by the University of Iowa on the 3M House and 3M Vienna single-channel systems, and The University of Melbourne/Nucleus and Utah multiple-channel systems (Tyler et al., 1987, Gantz et al., 1987). The 3M House system had the speech waveform modulating a 16 kHz carrier on a monopolar electrode, the 3M Vienna system a spectrally weighted waveform on one of four common-ground electrodes, and the Utah system bandpass filtered waveforms on six monopolar electrodes. The results showed significantly better speech perception performance for the multiple-channel systems, and although the performances of The University of Melbourne/Nucleus and Utah devices were comparable in quiet the Utah device performed better in noise from multi-speech babble. It was thought this performance difference in noise was due to the difficulties a preprocessing system such as The University of Melbourne/Nucleus device would have in selecting speech from noise, whereas the Utah system which presented the unprocessed output from six fired bandpass filters would have the patients brain differentiate the speech signals. While the FDA clinical trial and comparative evaluation of The University of Melbourne/Nucleus FO/F2 speech processor were being undertaken we were actively involved in psychophysical and speech research to improve our cue-extraction speech processing system.

As our previous research had shown the need to provide additional information to improve consonant perception, in particular, the next question to be answered was whether the presentation of the first and/or third formants as well as the second formant would improve intelligibility. It was also necessary to establish by research in our laboratory that improvements were possible before industry could direct its resources to producing an alternative wearable speech processor for patient evaluation.

Consequently, the first task was to determine whether the presentation of two stimuli near-simultaneously (0.5 ms separation between pulses to avoid unpredictable current summation) on a place coding basis would result in a single or two component sensation. It was argued that if we were to convey speech information containing two or more formants the brain should have the capability of perceiving additional information from a second stimulus channel.

The perceptual dissimilarities among ten two-electrode stimuli were estimated by triadic comparisons and the resulting matrices analyzed by non-metric multidimensional scaling (Tong et al., 1983b). This showed a two dimensional solution to be the best, indicating that the dissimilarities between two electrode pairs differing in both apical and basal electrodes was even greater than the sum of two component dissimilarities. These results suggested that two electrode stimulation was perceived as a sensation with two components, and could therefore be used to present speech information with two components, such as the first and second or the second and third formants.

To assess the value of using a speech processing strategy presenting two formants we developed an acoustic model of electrical stimulation on normal hearing subjects (Blamey et al., 1984a). The acoustic model was especially necessary as all our implanted patients were involved in the clinical trial for the FDA. Multiple-channel electrical stimulation was modelled with a set of bandpass filtered noise stimuli and gave similar psychophysical results on normal hearing subjects as pulsed electrical stimulation had given on the first two implant patients (Blamey et al., 1984a). The speech perception of the two multiple-channel implant patients when using the FO/F2 strategy was then compared with that of the normally hearing listeners when using an acoustic model of the FO/F2 strategy (Blamey et al., 1984b). 22 different speech perception tests were used and very good agreement found for the two groups of subjects indicating that the acoustic model could be a useful tool for the development and evaluation of alternative speech processing strategies.

It was considered preferable to initially compare the FO/F2 strategy with one that presented the first rather than the third formant in addition to the second formant as there was good evidence from the acoustic literature that the lowest two formants were at least the most important features for recognizing a vowel (Delattre et al., 1952). The study (Blamey et al., 1985) in fact showed a significant difference between the FO/F2 and FO/F1/F2 strategies for the vowel but not the consonant test. However, with consonant confusions there were improvements in information transmission for voicing (34% to 50%), nasality (84% to 95%) and affrication (32% to 40%) but not for place (28% to 28%). We also discovered that the consonants could be classified according to the amplitude envelopes of the F2 filter output, and this also improved for the FO/F1/F2 strategy. The improved vowel perception and increased information transmission for consonant features probably accounted for the significant improvement obtained in understanding running speech as shown with the speech Tracking test.

Having shown with the acoustic model that improved speech perception scores occurred for the FO/F1/F2 compared to the FO/F2 strategy a decision was made by industry to implement it as a wearable speech processor and this is known commercially as WSPIII. When this was clinically trialed on implant patients (Clark, 1986; Dowell et al., 1987) speech perception results were similar to those obtained with the acoustic model. This showed the benefits of coding first and second formants on a place basis, and the predictive value of the model. In quiet the closed-set medial vowel scores improved from 51% to 58% and the consonant scores from 54% to 67%. The mean open-set CID sentence scores three months postoperatively increased from 16% to 35% (Dowell et al., 1987). Improved speech results in noise were also achieved by the addition of the first formant, and they were comparable to those for the fixed filter strategy of the Utah multiple-electrode system (Dowell et al., 1987).

To further improve speech perception, especially for consonants, it was next considered appropriate to code additional information in the high frequencies on a place basis. Rather than use the third formant as we had originally proposed, we presented the filter outputs on a place coding basis in the ranges 2000-2800Hz, 2800-4000Hz and 4000-6000Hz for unvoiced sounds and two of these for voiced sounds. As initial results with this strategy showed improvements over the FO/F1/F2 strategy (Dowell et al., 1990), it was implemented by Cochlear Pty. Limited as a wearable unit and an independent comparison made for the FDA by Skinner et al., (1991). This strategy is known commercially as Multipeak-MSP.

An independent comparative study (Cohen et al., 1993) has recently reported speech perception results for the single-channel 3M Vienna, the multiple-channel Ineraid device (previously referred to as the Utah strategy), the multiple-channel Nucleus WSPIII (previously referred to as the FO/F1/F2 strategy), and the multiple-channel Multipeak-MSP device. The results confirmed the previous findings of Gantz et al., (1987) and Tyler et al., (1987) that the multiple-channel devices were superior to the single-channel system. Furthermore, open-set speech perception scores were significantly better for the Multipeak-MSP device than WSPIII. The mean open-set sentence score for WSPIII was 32% (range 2 to 76%) and for Multipeak-MSP 58% (range 9 to 97%). The open-set scores for Multipeak-MSP patients were also significantly better than for the Ineraid device (Cohen et al., 1993).

Space does not permit a summary of the research that has been undertaken to apply the FO/F1/F2 and Multipeak strategies to children, and those who are prelinguistically deaf, (born deaf or lost hearing before developing language) on the biological research to ensure the device is safe for children under two years of age. There is also not space to summarize our recent psychophysics and speech research which is showing that a strategy which extracts the six spectral maxima and presents these on a place coding basis, with amplitude modulation of a constant rate to convey voicing, is giving better results than the Multipeak-MSP device. Psychophysical and speech research in adults with cochlear implants in both ears is providing useful basic information and showing benefits in hearing speech in the presence of noise. Research to combine information presented by electrical stimulation to a cochlear implant in one ear and sound to a speech processing hearing aid in the other ear is also looking promising.

ACKNOWLEDGEMENTS

This research was a team effort and I would like to acknowledge support from my colleagues. This research would not have been possible without funding from a number of bodies which include the National Health & Medical Research Council of Australia, the Australian Research Council the Commonwealth Department of Employment Education and Training, the Commonwealth Department of Science and Technology, the US National Institute of Health, the Channel 0 (10) Telethon and Nerve Deafness Appeal and Lions International.

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NEWS... NOTES... PEOPLE... BOOKS... PRODUCTS

Commission on Heliport

A Commission of Inquiry for Environment and Planning, set up under the NSW Planning and Assessment Act to examine and make recommendations in respect of the environmental aspects of a proposed heliport at Pier 8 Pyrmont, has recommended to the Minister that approval be granted to the heliport, subject to conditions.

In 1991, the Maritime Services Board (MSB) sought tenders for the operation of a heliport at the Pyrmont site, to serve the Central Business District of Sydney. The successful tenderer was the Helicopter Association of Australia (HAA). An Environmental Impact Statement (EIS) was prepared, using as a basis the noise acceptability criteria from Appendix A of Australian Standard AS 2363. That standard had been adopted by State Cabinet and the MSB, but the criteria were not considered appropriate by the NSW Environmental Protection Authority (EPA). The establishment of the Commission of Inquiry resulted from a motion of the State Legislative Assembly.

The dominant environmental issue was the alleged adverse noise impact of helicopter operations on the residential amenity of surrounding localities such as Balmain, Pyrmont and North Sydney. Allied with that issue was the question of the appropriate noise assessment method to be applied. Seven hundred written submissions were received by the Commission, and 48 submitters presented oral evidence at hearings in May and June.

Based on AS2363, the proposal sought approval for a maximum of 60 helicopter movements per day Monday to Saturday between the hours of 7:00am and 7:00pm, and 45 movements between 9:00am and 5:00pm on Sunday. A maximum number of 1,500 movements over a thirty day period was also proposed in conjunction with the daily limits. A movement is either a take off or a landing by a Bell 206 JetRanger or its acoustical equivalent.

Submissions to the Commission proposed that a variety of assessment methods be used, including AS2363, the NSW EPA Guidelines, the Australian Noise Exposure Forecast (ANEF) system, and a number of variants of the British NNI system. The Commission estimated that the permissible number of helicopter operations per day which would result from the application of the various acceptability criteria ranged from 3 to 1,130. The Commission also received submissions that any helicopter operations at all would be too many.

In its recommendations on the appropriate noise criteria, the Commission rejected the EPA Guidelines and AS2363, and adopted the ANEF method, in particular ANEF20 (approximately 55 dBA Leq 24 hour) as the acceptable criterion for residential use. The Commission's reasons for so doing included the following:

- the ANEF method is based on research into aircraft noise carried out in Australia;
- it is consistent with the criterion used by the Civil Aviation Authority in assessment of the noise from helicopters using the Sydney Harbour helicopter transit lane R409 (which is used by helicopters arriving at and departing from the heliport) and thus there is no anomalous position of two different noise criteria applying within the same airspace;
- no compelling evidence was presented to suggest that helicopter noise should be treated differently from noise of conventional aircraft;
- it is consistent with World Health Organisation recommendations for noise in residential areas; and
- it provides a proper basis for future monitoring of the heliport.

The Commission recommended that 48 helicopter movements per day be permitted Monday to Saturday between 7:00am and 7:00pm, and 24 movements per day on Sundays and Public Holidays between 10:00am and 4:00pm.

It also recommended the setting up of a complaints telephone service, the logging of all operations at the heliport, noise monitoring to be undertaken over a period after the opening of the heliport, and the establishment of a Special Monitoring Committee with local government and community representatives, to monitor operation of the heliport and compliance with the conditions of operation.

Leigh Kenna

Open Air Concerts

NSW Division members were privileged to hear from five speakers at a mini-seminar preceding the AGM of the Division.

Alex Jochelson (EPA) set the scene with details of the types of controls now being applied to open air concerts at the Sydney Showground, the Sydney Cricket Ground, the Sydney Football Ground, the Domain and the Parramatta Stadium.

Peter Knowland (acoustical consultant) detailed the changes that have occurred over the past few years, the problems with fold back monitors, the wasted sound that should be entertaining the audience but is annoying the neighbours, and the use of Lmax controls for quick response to over-loudness.

John Thompson (sound consultant) indicated the trends taking place for sound control at the venues, and the awareness of the promoters of the need to satisfy the audience whilst not annoying neighbours.

Noel Neate and **Laurie Jackson** gave the venue operators point of view, particularly with respect to the social acceptance of outdoor concerts overseas, the requirement for venues with crowd capacity in excess of 40,000 persons, and the need to allow a number of concerts at particular venues with established criteria.

Subsequent questioning from the assembled audience indicated quite clearly the interest in the subject. If there had not been the need to proceed with the AGM, the discussion would have continued unabated, but sadly had to be brought to a close by the Chairman.

Tony Hewett

More Neighbourhood Engineers

The October 1993 issue of the Institution of Engineers Sydney Division Newsletter, included the following call:

"We have had requests for more Neighbourhood Engineers for the Sydney Region. If you are interested in helping students and the community to be aware of Engineering as a profession, please call Karen on (02) 929 8544." Karen Yu is the Manager of Young Engineers Services at the Institution.

Acoustical engineers within the Society may consider assisting, and furthering the Society's aims at the same time?

Quality Management

A new quality certification program has been developed by Standards Australia Quality Assurance Services (SAQAS) specifically for small businesses. The Core Quality Program provides entry level certification through d-i-y implementation. The program ensures the basic concepts of quality - fitness for purpose and customer satisfaction - are established throughout the enterprise. This program will enable small business in Australia to take up the challenge of quality management systems. For more information contact SAQAS on (02) 746 4909, Fax (02) 746 4954.

Worksafe Video Wins Honourable Mention

The Worksafe Australia video, "Noise Management at Work", has won an honourable mention at the 2nd international film and video festival held at the Thirteenth World Congress on Occupational Safety and Health in New Delhi.

Moves

Acoustic Research Laboratories Pty Ltd has announced the appointment of **Ken Williams** to the position of Manager. Until recently Ken has served in the Royal Australian Navy in positions involving the management of noise and vibration measurement equipment and procedures.

Acoustic Research Laboratories Pty Ltd has appointed Machinery Monitoring Systems Ltd as its sole New Zealand agent for the Enviro-Log range of noise and vibration loggers. MMS may be contacted at 3/355 Manukau Rd, Epsom, Auckland 1003 NZ.

Vipac Engineers and Scientists moved their Sydney office in mid November. Their new address is Unit E1-B Centrecourt, 25 Paul St Nth, North Ryde, NSW 2113; Tel (02) 805 6000, Fax (02) 878 1112.

Sarah Banks and **Dan Dang** have been appointed as acoustical engineers for Mitchell McCotter.

✦ ✦ ✦

NEW MEMBERS

The following are new members of the Society, or members whose grading has changed.

New South Wales

Subscriber
Mr A Appleby
Mr G A Leembruggen
Dr J A Ogilvy
Mr R O Stevens
Mr K F S Wong

Queensland

Student
Ms H J Nave

Western Australia

Member
Mr M J Limb

Subscriber
Mr D J Lloyd

AUSTRALIAN ACOUSTICAL SOCIETY
1994 CONFERENCE

NOISE AND SOUND:
Nuisance and Amenity

9-11 November 1994
CANBERRA

The call for papers and expression of interest for the 1994 Conference has been released.

Details: Marion Burgess,
Acoustics and Vibration Centre,
ADFA, Canberra, ACT 2600.
Tel (06) 268 8241
Fax (06) 268 8276
email m-burgess@adfa.oz.au.

Books . . .

SIGNAL PROCESSING OF SPEECH

F.J. Owens

Macmillan, 1993, paperback, 179 pp. ISBN 0-333-51921-1. Aust. distributor: Macmillan Australia, 107 Moray St. Sth Melbourne 3205 Tel (03) 699 8922; Fax (03) 690 6938. Price A$39.95

This book is one of a series designed for "optional" courses in the final year of an electronics engineering degree, but it can also serve as an admirable introduction to the subject for engineers or scientists in neighbouring fields. Speech processing is an area of current importance, and the level of treatment in this book is sufficiently detailed that the reader comes to appreciate the nature of the technical achievements and the obstacles still to be surmounted.

After an introductory chapter on the nature of speech and hearing, the emphasis shifts to the technical problems of encoding speech in some form that greatly reduces signal bandwidth requirements but still allows reconstruction of the basic speech sounds. Both the analysis and synthesis phases of this problem are treated, and the algorithms underlying several different approaches are clearly explained. Parametric analysis and feature extraction are both discussed, without too much algebraic detail. One ultimate aim of speech processing is, of course, the direct recognition of speech by computers, and this problem is treated in the final two chapters, with emphasis on dynamic time warping and hidden-Markov models.

It is possible to read this short book in the course of a few nights or to study it more deeply. The writing is clear and straightforward, and there are only a few places in which the details of the coding algorithms induce one to skip a page or two – of course this detail is valuable for those with a more serious engineering interest in the techniques. There is a short bibliography of about thirty items, mostly classics in the field. I can recommend this book to anyone with a physics or engineering background as a very good way to get an overview of this important area of research and development.

Neville Fletcher

Neville Fletcher is a chief research scientist with CSIRO. His research interests cover a wide range in acoustics and applied physics.

ACOUSTICS FOR ENGINEERS

J.D.Turner & A.J. Pretlove

Macmillan, 1991, paperback, 192 pp. ISBN 0-333-52143-9. Aust. distributor: Macmillan Australia, 107 Moray St. Sth Melbourne 3205 Tel (03) 699 8922; Fax (03) 690 6938. Price A$31.95

Considering its small size and depth of coverage, this book is intended to be an introduction to the basic principles of acoustics and noise control. It is aimed at engineers who might find themselves in the position of having to deal with noise problems in application or design, and also at student engineers who are more likely than previous generations to encounter acoustics as part of an undergraduate degree. In this context, it must be said that the book succeeds fairly well, in giving at least a qualitative appreciation of a wide range of important concepts, and in the main, references to where particular subjects are treated in more detail. It is divided into eight chapters, covering respectively, Basic concepts of noise and vibration, The human effects of noise: criteria and units, Sound in three dimensions (one-dimensional propagation having been treated in chapter 1), Analysis of acoustic and vibration signals, Digital methods of spectrum analysis, Acoustic instrumentation, Reflection and transmission: Sound in confined spaces, and finally Noise control.

The first chapter sets the tone for the theoretical treatment of a number of topics in the book. Even though it starts by deriving a partial differential equation (the one-dimensional wave equation) it does it for the simplest case (longitudinal stress waves in a solid bar) and then extends this to pressure waves in a uniform tube, deriving an equivalent Youngs modulus from consideration of adiabatic compression. Using the simple one-dimensional case, general principles about acoustic impedance and power flow are illustrated. Analogies with simple electrical circuits are made which will assist engineers more familiar with that topic. Likewise the treatment of three-dimensional sound fields in Chapter 3 starts with the three-dimensional wave equation, but quickly simplifies it to spherical waves with which the concepts of complex impedance and near vs far field can be introduced. The directivity of a microphone is derived for a rectangular membrane to avoid having to deal with Bessel functions, it being explained that the results are qualitatively very similar for a round membrane. The importance of physical dimensions vs wavelength is emphasised, including examples of where simplifying assumptions can be made to model sources as simpler ones.

The discussion of basic vibration theory in Chapter 1 is concise but thorough for single degree of freedom (SDOF) systems, covering dynamic magnification and isolation and once again emphasising general principles, such as when the vibration is stiffness, mass, or damping controlled. Continuous systems are treated briefly by showing how SDOF equivalents can be obtained for the first (and generally most important) mode of beams and plates. Understanding of this section would be improved by use of an example. In this connection, there is an unfortunate error in the equation for the relative stiffening of plates with respect to beams where I, immediately defined after as a second moment of area, is given instead of 1. This was one of very few errors which were found.

In general where topics are not treated in full (and that after all covers most of the book), references for further reading are given. This was not the case, however, for the topic of assessment of community noise annoyance for which a procedure is outlined in Chapter 2. No reference is given, though there is a remark about criteria "originally derived from research in the Netherlands". This compares with two references about aircraft noise.

The chapter on acoustic and vibration analysis is a conventional treatment of Fourier series analysis, with extension to the Fourier transform by allowing the period to go to infinity. This is the only place where the difference in dimensions between the spectra of continuous and transient signals is mentioned. Elsewhere, spectra are described loosely as representing spectral "energy", even where "power" might be more appropriate, and this might be confusing for the uninitiated. It is a pity that random signals are not treated at all, in particular the different spectral levels that random and discrete frequency components will have, depending on bandwidth.

The chapter on "digital methods of spectrum analysis" should really be called "FFT methods", as digital filter methods are not mentioned. This is also a pity, as digital filters are definitely the most efficient (and economical) way to achieve realtime constant percentage bandwidth analysis over the acoustic frequency range (eg simultaneous measurement of reverberation time in all 1/3 octave bands). The discussion of acoustic instrumentation in the next chapter is also somewhat out-of-date, despite the claim about "modern measurement techniques". The only instruments pictured, a sound level meter and an FM tape recorder, are both about 15 years old, though of course still able to produce valid results. In particular, the guidance as to tape recording methods is not fully valid, as digital recorders are said to be "much more expensive than analogue systems" whereas two channel DAT recorders are now considerably cheaper than comparable FM or Direct recorders, while 4-8 channel instrumentation DAT recorders are comparable in price, with better technical specifications. DATs provide the only possibility, for example, for recording signals from an intensity probe, because of their vastly superior phase matching between channels. One thing which perhaps should have been included in this chapter, is some discussion of the effects of averaging time (even "fast" and "slow" response are not mentioned anywhere). This leads to some confusion as to the meaning of "peak value" which is used rather loosely in different places to mean different things, sometimes a peak instantaneous value and sometimes a maximum RMS value (which would depend greatly on the averaging time).

The chapter on FFT analysis gives quite a good discussion of two of the major pitfalls, viz aliasing and leakage, but does not mention the third, the picket fence effect, which can be important when calibrating a system using a calibration tone.

The final chapter, on noise control, ties together information from the rest of the book and outlines a logical method for tackling noise reduction problems, which should be of great assistance to people starting in the field. The method allows prediction of the likely results, and cost, of the various control measures which might be applied. As in many other sections dealing with the application of the basic theory to practical problems, examples are given based on the authors' own experience.

Despite the above criticisms, which are not as serious as the space devoted to them might suggest, I found the book to be very readable and enlightening, and am sure that newcomers to the field will find it particularly so.

R.B.Randall

Bob Randall is a Senior Lecturer in the School of Mechanical and Manufacturing Engineering at the University of New South Wales, specialising in vibration analysis and machine condition monitoring. Prior to joining the university he worked for Bruel & Kjaer for 17 years.

ACOUSTIC SYSTEMS IN BIOLOGY

N. H. Fletcher

Oxford University Press, 1992, pp 333, hard cover ISBN 0-19-506940-4. Aust Distributor: Oxford University Press, GPO Box 2784Y, Melbourne 3001, Tel (03) 646 4200, Fax (03) 646 3251. Price A$110

This book is concerned with the acoustics of the processes of sound generation and reception by animals. It is an acoustic rather than a biological text, yet the overall aim is to provide an understanding of the biological systems that make use of sound, by developing acoustic models of such systems.

According the preface, the book is written primarily for biologists with an interest in acoustic systems, and the author suggests that it might be suitable for a one semester course for biologists at graduate level. He also suggests that it should also be suitable for a similar course for physics or engineering students at advanced undergraduate level. My impression, as an acoustician interested in bioacoustics, is that the book will be as useful for acousticians as for biologists.

The author points out that biologists are poorly served when it comes to acoustic

texts - they are either too elementary or too mathematical. This accords with my own experience in working with biologists, especially post graduate students - most acoustics texts expect the understanding of acoustics to come from understanding the mathematics, and as Neville Fletcher states, biologists are not traditionally well trained in mathematics. This of course is by no means one sided - physicists tend to be poorly trained in biology and find it just as difficult to cope with many biological works.

"Acoustic Systems in Biology" is intended as a text book and assumes no prior knowledge of acoustics. A limited amount of mathematical knowledge and technique is required, but the mathematics is kept to the essentials for understanding the mathematical models of biological systems without compromising rigour. Even so, readers should expect to deal with a fair amount of mathematics since that is the nature of the subject. However, the author takes pains to explain, interpret and "de-mystify" the mathematics and relate it to the physics, and to provide the insights that come only from a thorough understanding of the subject. This approach should make it much more accessible to biologists than other acoustics texts. Someone with a knowledge of differentiation and integration should be able to follow the mathematics. Familiarity with differential equations is not necessary (though course, it would make the going easier).

The first chapter sets the stage by comparing the approaches of physics and biology, and by providing the non physicist with an insight into the nature of mathematical models, their construction and what we should expect of them. This is a nice introduction of general interest.

The book covers the basics of acoustics appropriate to bio-acoustic systems and develops this knowledge as required to understand the mathematical models of such systems, and then presents, analyses and interprets the models. The "basics" follows conventional themes - simple vibrators, strings and bars, membranes and plates, acoustic waves, sources and radiation, pipes and horns etc., but with the underlying focus on biological systems and inclusion of references to biological examples. There is then extensive treatment of acoustic systems including auditory models, the inner ear and mechanically and pneumatically excited sound generators. The book also includes some discussion of network analogs and a limited discussion of communication and information theories applied to animal communication and sonar.

To an acoustician, the book will seem like an acousticians guide to bioacoustic systems, because it is written like an acoustics text book and does not require much, if any, biological knowledge. I bought the book because I thought it might help me understand sound generation and reception in animals. The more I read this book, the more I find it suits my needs. It brings together in one book what I would otherwise have to search far and wide for, and it brings out the underlying acoustics in a way that is not evident in the more biological texts. Acousticians do not have to read the bits on basic acoustics if they do not want to (better still they do not have to admit reading them - I suspect that there are acousticians like me who would find this part of Neville Fletcher's text a refreshing revision of things we ought to know but have forgotten, with perhaps some new insights thrown in).

But what of the biologists? Well, the book is tailored to the needs of biologists interested in acoustic systems, and the style of presentation goes a long way to making acoustics accessible. Some, like those whose mathematics skills have faded through lack of use and those who never really developed much skill by being clever enough to avoid mathematics while studying biology, may find even this presentation of the mathematics difficult. My advice is that if you are seriously interested in acoustic systems then any effort you put into understanding the models in this book will be well worth while. You have to work at the mathematics, but that is true for most of us (I am told that even Einstein had difficulty with his mathematics). The author has done a lot to make it accessible in a way that is not otherwise available. Others with a less intensive interest in the subject will find that the non-mathematical synopsis at the beginning of each chapter provides a good summary and it is possible to get a lot from the reading text without understanding the equations.

This book does not cover any more biology than is required to understand the acoustic models - it rightly, in my view, leaves that to the biological texts. It does not cover all aspects of bioacoustics - it focuses on those aspects dealing with the acoustic systems discussed above. Again this seems appropriate, and consistent with the title. At the same time it covers a sufficiently broad range of acoustics to be useful as a basic acoustics text.

Science is very much compartmentalised and it is difficult to cross disciplines or to find books that do so. "Acoustic Systems in Biology" is a significant contribution because of its value to both biologists and physicists, and I know of no other text that covers the subject matter. It is well written and gives a good feeling for the physics that should appeal whatever the reader's discipline.

Doug Cato

Doug Cato is a Principal Research Scientist in the Materials research Laboratory of DSTO, Sydney. His research interest is the ambient noise in the ocean including the use of sound by marine animals.

PROCEEDINGS OF THE THIRD INTERNATIONAL WORKSHOP - Transducers for Sonics and Ultrasonics.

M. D. McCollum, B. F. Hamonic and O. B. Wilson (Editors)

Technomic Publishing Company, 1992, pp402, hard covers, ISBN 0 88762 993 5. Technomic Publishing Co, 851 New Holland Ave, Box 3535, Lancaster, PA 17604, USA. Price US$165.

This book consists of the proceedings of the Third International Workshop on Transducers for Sonics and Ultrasonics held in Florida in May 1992. The editors introduce this series of meetings as a forum for researchers in the area of transducer development. The range of topics under consideration is determined by the recent developments in transducer technology with the aim to look at the future trends.

The reviewer already had the proceedings of the first workshop. The first workshop focussed on power transducers only. Despite the limited scope of the topic the book was an invaluable tool for someone involved in underwater transducer design. The main reason for the value of such a volume is that there is relatively little published on the topic of transducer design in book format. The present volume has the scope broadened from that of the first workshop and is essential for anyone desiring to keep abreast of the latest developments in transducer technology. The primary topics of the sessions were: transduction materials, projectors and hydrophones for sonic and ultrasonic applications and transducer modelling. The book is divided into three sections: invited papers, contributed papers and poster papers.

The invited papers were prepared by acknowledged leaders in the area of transducer technology and takes up about one third of the book. It is worth briefly describing the contents of each of these invited papers as it gives a flavour of the contents of the volume as a whole. The first invited paper is by Robert Ting on "Recent Developments in Transduction Materials for Future Sonar Transducers". At present the topic of materials for use in sonar sensors is one of great interest all around the world due to the fact that new submarine development allows higher speeds and greater depth capability than previously possible and that submarines will be conformally coated with sonar sensing materials. This leads to new requirements for sensors. The operational conditions for the new generation of submarines which determine the material requirements are discussed by Ting.

Over recent years a number of materials have come to the forefront as contenders sonar applications. The materials have been known of for some time but it is only recently that manufacturing technology has made it possible to produce large quantities at reasonable cost. The modelling of these materials is also becoming more reliable. Ting reviews the main materials of interest: Lead Titanate, piezocomposites 0-3 and 1-3 and electrostrictive ceramics. The papers in the book do not concentrate on material properties but rather the application to hydrophone design. In the contributed and poster papers other types of hydrophone materials are investigated. There are also investigations of hydrophones made from magnetostrictive material (terfenol), PVDF and optical fibre. The advent of new material technology does not mean that the traditional ceramics for sonar applications such as PZT no longer have application. There are a large number of papers on hydrophones and projector designs based on PZT.

A paper by D. Boucher is titled "New solutions for Low Frequency Sonar Projectors" reviews transducers based on the Tonpilz and Flextensional design. Again the interest in low frequency active sonar is driven by military requirements. New submarines are quieter than ever before and hence harder to detect. Active sonar is now needed to detect these quiet submarines. Low frequency transducers, which must be compact in size, are needed to achieve large detection range. The book reflects this requirement as there are a total of 10 papers on the modelling and design of flextensional transducers. An invited paper by E. Rynne is titled "Innovative Approaches for Generating High Power, Low Frequency Sound" reviews flextensional transducer design and discusses the importance of modelling to progress from design concept to system application.

Transducer modelling is the topic of the paper by G. Benthien titled "The Direction of Transducer and Array Modelling in the 1990's" which surveys simple one dimensional transducer models and the more sophisticated finite element methods. There are several contributed papers on the finite element method and these show that this technique is coming into its own in piezoelectric transducer design. Several papers investigate the modelling of flextensional transducers. The sixth invited paper by A. Hladky-Hennion titled "Modelling of Active and Passive Periodic Structures" addresses the problem of modelling 1-3 composite structures.

A paper which deals with acoustic sensors fabricated using similar technology as that used in the manufacture of integrated circuits is by J. Bernstein and titled "Micromachined Acoustic Sensors".

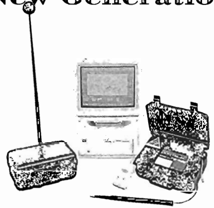
The poster paper section consists of articles each roughly four pages. These tend to deal with experimental techniques and were found by the reviewer to be particularly useful. Several of the papers described useful techniques in transducer measurement. This is the sort of information that does not get published in books and one generally needs to attend conferences to get this information. Another covers thermoacoustic devices which are capable of generating low frequency sound by a thermal to acoustic energy conversion process.

This book gives a feel for what is happening around the world in transducer research and what applications are driving the research effort. It is of definite value to those involved in transducer design and to some extent all those involved in sonar. However the audience to which this applies will be limited. The focus is on military applications, the meeting being hosted by the U.S. Naval Research Laboratories. Today commercial applications of sonar are getting more attention as companies diversify and so the technology will flow through to other areas. Generally the papers are easy to read and most are written very concisely.

In summary the book is of value to anyone trying to find what is happening at the present time in transducer technology. It gives a good feel for where research effort may best be directed. The book will have limited general readership but is essential for those working in the relevant disciplines.

Andrew Madry

Andrew Madry completed a PhD at Sydney university on outdoor sound propagation. He has worked for a number of years on DSP for video communications. He currently works at GEC Marconi Systems as an acoustician involved in testing and transducer design for underwater defence systems.



Publications by Australians . . .

The following listing of publications by Australian authors is provided in order to encourage communications among those working in the various fields of acoustics.

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Torsion response and vibration suppression of wind-excited buildings. AU Xu, Y.L. (Univ of Sydney); Kwok, K.C.S.; Samali, B. *J. Wind Engineering & Industrial Aerodynamics v 43 pt 3 Oct 1992.p 1997-2008*

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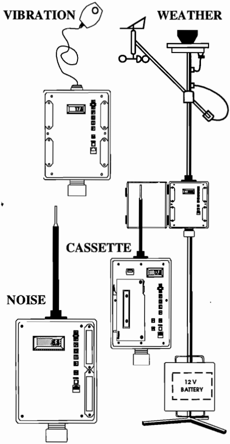
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Further information: Bilsom, 19 Tepko Rd, Terrey Hills, NSW 2084. Tel (02) 450 1544, Fax (02) 486 3319

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CONFERENCES and SEMINARS

* Indicates an Australian Activity

1994

February 27 - March 3, AMSTERDAM
96th AES
Details: Sec, AES Europe Office, Zevenbunderslaan 142/9, B-1190 Brussels, Belgium

May 1-4, FORT LAUDERDALE
NOISE-CON 94
Details: Susan Fish, Department of Ocean Engineering, Florida Atlantic University, 500 NW 20th Street, Boca Raton, FL 33431 USA. Tel (407) 367 3430, Fax (407) 367 3885, e-mail: fish@oe.fau.edu

May 15-19, PERTH
* MECH 94 - Resource Engineering including tri-annual Australian Vibration and Noise Conference
Details: Convention manager,Mech 94, AE Conventions, Engineering House, 11 National Circuit, Barton, ACT 2600, Tel (06) 270 6530, Fax (06) 273 2918

June 5-9, CAMBRIDGE
127th Meeting Acoustical Society of America
Details: Acoustical Society of America, 500 Sunnyside Boulevard, Woodbury, NY 11797, USA

July 3-7, HALIFAX, NOVA SCOTIA
22nd International Congress of Audiology
Details: Secretariat, PO Box 2627, Station M, Halifax, Nova Scotia, Canada B3J 3P7. Tel (902) 461 0230, Fax (902) 465 2233.

July 18-21, SOUTHAMPTON
5th International Conference on RECENT ADVANCES IN STRUCTURAL DYNAMICS
Details: ISVR Conference Secretariat, The University, Southampton, SO9 5NH, England.

August 23-25, SEOUL
WESTPRAC V
Details: The Acoustical Society of Korea, Science Building, Suite 302, 635-4 Yuksam-Dong, Kangnam-Ku, Seoul 135-703, Korea. Tel 82-2-556-3513, Fax 82-2-569-9717.

August 29-31, YOKOHAMA
INTERNOISE 94
Details: Yoiti Suzuki, Sone Lab, RIEC, Tohoku Univ. 2-1-1 Katahira, Aoba-Ku, Sendai, 980 Japan. Tel 81 22 266 4966, Fax 81 22 263 9848, email: in94@riec.tohoku.ac.jp

August 31 - September 3, YOKOHAMA
2nd International Conference on Motion and Vibration Control
Details: Assoc Prof Kazuo Yoshida, Secretary of 2nd MOVIC, Faculty of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223, Japan. Fax +81 45 563 5943.

November 9-11, CANBERRA
* AAS Annual Conference 1994
Noise and Sound: Nuisance and Amenity
Details: Marion Burgess, Acoustics and Vibration, ADFA, Canberra, ACT 2600. Tel (06) 268 8241, Fax (06) 268 8276, email m-burgess@adfa.oz.au.

November 28 - December 2, AUSTIN
128th Meeting Acoustical Society of America
Details: Acoustical Society of America, 500 Sunnyside Boulevard, Woodbury, NY 11797, USA

December 5-7, SYDNEY
* International Conference on Acoustic Imaging and Remote Sensing
Details: John Dunlop, School of Physics, U.N.S.W.,PO Box 1 Kensington, NSW 2033 Tel (02) 697 4575 Fax (02) 663 3420, email jid@newt.phys.unsw.edu.au

1995

May 31 - June 4, WASHINGTON
129th Meeting Acoustical Society of America
Details: Acoustical Society of America, 500 Sunnyside Boulevard, Woodbury, NY 11797, USA

June 26-30, TRONDHEIM
15th International Congress on Acoustics
Details: ICA'95, N-7034, Trondheim, Norway.

July 10-12, NEWPORT BEACH, CALIF
INTERNOISE 95
Details: INCE/USA, PO Box 3206 Arlington Branch, Poughkeepsie, NY 12603 USA. Fax +1 914 473 9325

November 27 - December 1, ST LOUIS
130th Meeting Acoustical Society of America
Details: Acoustical Society of America, 500 Sunnyside Boulevard, Woodbury, NY 11797, USA

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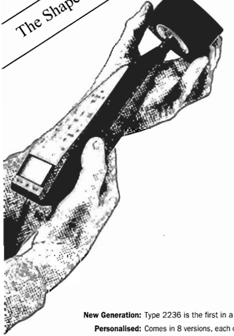

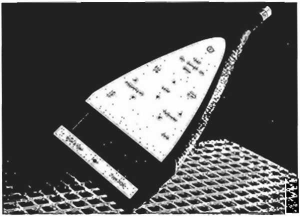

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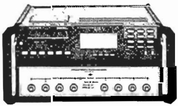

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