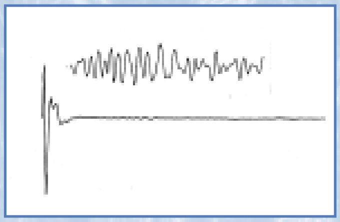
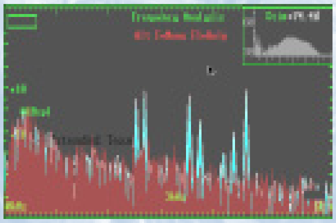
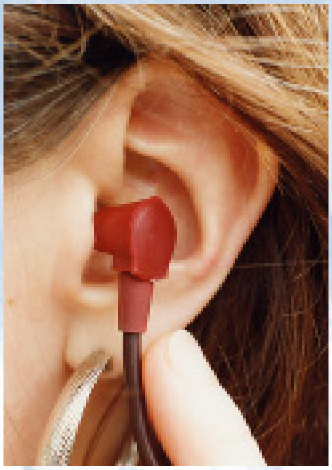


The OAE Story





An illustrated history of OAE research and applications through the first 25 years

by David T. Kemp

David Kemp is Professor of Auditory Biophysics at University College London. In 1977 he discovered the otoacoustic emission phenomenon in laboratories at the Royal National Throat Nose and Ear Hospital, Gray's Inn Road London, adjacent to the Institute of Laryngology and Otology - the ILO. Much of the pioneering laboratory research on otoacoustic emission was conducted at the ILO, and the ILO88 instrument also originated there. Dr. Kemp has received several awards for his work on otoacoustic emissions. In February 2003, he received the Award of Merit from the Association for Research in Otolaryngology.

In 2004 Dr. Kemp will join auditory scientists from across University College at the new UCL Centre for Auditory Research (shown below) which is currently being built in Gray's Inn Road.

UCL MEDICAL SCHOOL

The Institute of Laryngology & Otology, the UCL Centre for Auditory Research and the Royal National TNE Hospital

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What are Otoacoustic Emissions?

Otoacoustic emissions are sounds made by our inner ear as it works to extract the information from sound to pass on to the brain. These biological sounds are a natural by-product of this energetic biological process and their existence provides us with a valuable 'window' on the mechanism of hearing, allowing us to detect the first signs of deafness - even in newborn babies.

The organ of Corti and basilar membrane of the cochlea exposed *(Photo: A. Pye)*

Sounds made by healthy ears are quite small - quieter than a whisper and usually less than 30dBSPL. They arrive in the ear canal because the middle ear receives vibrations from deep inside the cochlea. This causes the eardrum to vibrate the air in the ear canal creating the sounds that we can record.

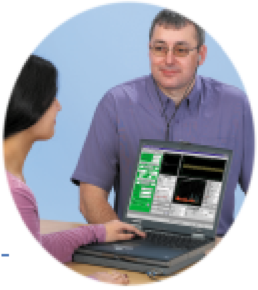
To record otoacoustic emissions, or 'OAEs', a 'probe' is inserted in the ear canal. The probe closes the ear canal, keeping the OAEs in and any noise out. The probe both stimulates the ear with precisely defined sounds and records the sounds made *by* the ear via a tiny microphone. Separating the applied sound from the ear's own sound is a delicate business and needs computer processing power.

OAE probes contain a microphone and sound producer

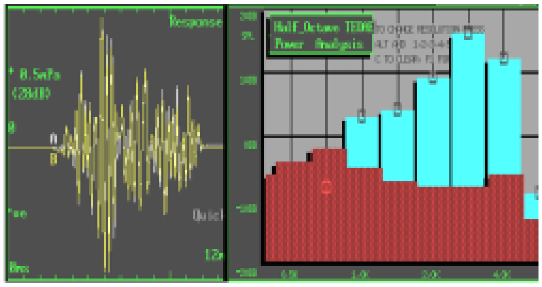
Today this is achieved by a variety of otoacoustic instruments. Hand-held and pocket-sized screeners are available which provide a quick indication of the status of the ear and are widely used for infant screening. Because OAEs are blocked by middle ear immobility, these instruments alert to both conductive and sensory dysfunction. Some OAE screeners provide a single indicator of function across speech frequencies, as does screening ABR. Others provide a basic frequency breakdown. Although OAE screeners are sensitive to threshold elevations as small as 20dB, they do not provide a measure of the actual threshold.

Simple OAE screening instruments conceal the fact that otoacoustic emissions are quite complex phenomena - whether they are evoked by tones or clicks. Click evoked OAEs (TEOAEs) consist of a complex response waveform which can be broken down into different frequency bands (typically half octave), telling us about cochlear status in each band. Distortion product OAEs are evoked by a pair of tones (typically one-third-octave apart) which are stepped across the frequency range to be examined. Each pair of tones may produce several DPOAEs. One of these (typically the one at 2f1-f1) is plotted on the 'DP gram'. Both TEOAEs and DPOAEs provide frequency specific data on cochlear function, the interpretation of which is discussed later.

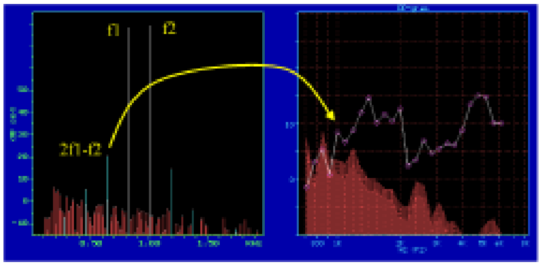
Hand-held OAE screeners are used in universal newborn hearing screening programs



OAE analysers are an important part of the autometric test battery



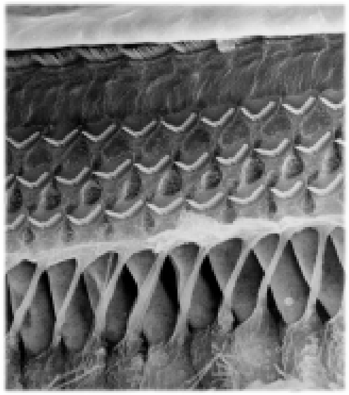
OAE is a complex phenomenon. Click evoked OAEs have complex waveforms (left) which can be broken down into component frequencies (right)



A pair of stimulus tones produce several DPOAEs (left). Typically the one at 2f1-f2 is plotted for different stimulus pair to form the DP-gram (right)

Why do our ears produce OAEs?

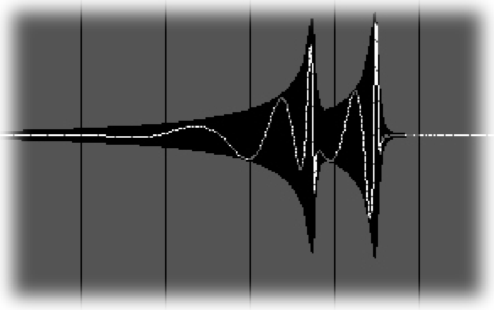
In all land animals hearing depends on collecting sound energy from the air and transferring it to water immersed sensory cells which then stimulate nerves leading to the brain. OAEs arise because our ears have evolved a special mechanism to give us extra hearing sensitivity and frequency responsiveness. The mechanism is known as the cochlear amplifier and it depends on a specialized type of cell called *outer hair cells*. All mammals rely on this same mechanism for hearing. Other animals have different mechanisms but most of these also produce OAEs in some form or other.



Sectional view of the organ of Corti. Outer hair cell bodies (lower) support stiff hairs which in life touch the tectorial membrane, here rolled back (top). Hairs of the inner hair cells (visible top) are sensitive to the flow of fluid across the organ. *(Photo: A. Forge)*

It's the job of the cochlea to receive the sound energy collected by the outer and middle ear and to prepare it for neural transmission. That's not a trivial matter.

Nerve fibres are rather unsuited to carry sound information. They rarely operate faster than 2kHz and yet mammals evolved with a need to hear much higher frequencies than this. The problem is solved in the cochlea by separating the frequencies comprising a sound before they reach the nerves and then presenting each frequency component to different nerves (30,000 of them) which fan out around the cochlear spiral. In this way the nerves only need to transmit the *intensity* of the sound at a particular frequency which they can do without having to carry the rapid oscillation of the sound itself. Their rate of firing conveys the intensity of the sound component.



The cochlear travelling waves move up the cochlear spiral delivering different frequency components to different places. Here two tones (moving from left to right) cause two separate peaks of activity.

Another problem with nerve fibres is that they can't signal a very wide range of intensities - maybe only a 1:100 range. This is just not good enough for hearing as the contrast between near and very distant sounds can be up to 100,000 times.

The cochlea overcomes this problem by boosting the quieter sounds we need to hear with its own biological amplifier. Actually it solves two problems at once. Although anatomically the cochlea is constructed to naturally separate frequency components along the length of spiral sensory organ, just as a prism separates the colours of light, the viscosity of water inside the narrow spaces of the cochlea damps down the sound induced vibration far too rapidly for this process to work efficiently. Unassisted, much of the sound energy in the cochlea would be lost to viscosity and the energy of each frequency component would be spread over too large a number of sensory cells. But, outer hair cells react mechanically to stimulation. They change length rapidly releasing their own vibration. Their electro-motile action replaces stimulus energy lost by viscosity and boosts the travelling wave inside the cochlea. This ensures that sharp frequency separation can develop and it particularly raises the intensity of the weaker sounds to that needed to activate auditory nerves.

The cochlea separates sound frequency components like a prism separates the components of light.

OAEs arise because some of the energy generated by outer hair cells leaks back into the ear canal. That's not important for hearing, but it is important for research and audiology as it provides us with a means of examining the health of the innermost parts of the cochlea from outside.

Before OAEs: Gold's idea of a cochlear amplifier

All mammals produce sound from their ears whenever external sounds stimulate the cochlea and in all probability dinosaurs' ears also did millions of years before - but this phenomenon was totally unsuspected by scientists before 1977.

George von Bekesy who first described the cochlear travelling wave

From the time when Nobel Prize winner George von Bekesy first explained how sound created travelling waves on the basilar membrane in the 1940s, there was a problem in auditory theory. The travelling wave separated frequency components in the cochlea but the degree of frequency separation seen by Bekesy in human ears post mortem was quite poor. In contrast, recordings made in auditory nerve fibres themselves showed that the healthy cochlea somehow managed to achieve sharp frequency division. Measurements of sound vibrations in living animal cochleae seemed to confirm Bekesy's findings, and the search began for a 'second filter' - a notional mechanism that would explain the extra frequency selectivity seen in the auditory nerve but not in the cochlea. It was never found.

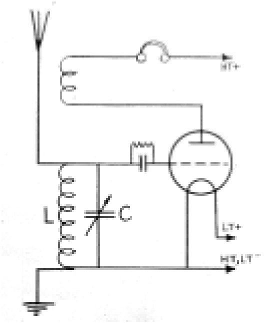
As early as 1948 one man, a contemporary of von Bekesy, Thomas Gold, put forward a startling new hypothesis. Comparing the function of the ear with that of the radio receiver, Gold argued that to achieve simultaneously both high sensitivity and high frequency selectivity there must be a biological vibration amplifier. As in primitive radio receivers, this extra energy could be applied as positive feedback to the travelling wave to overcome the natural viscous loss of energy.

Thomas Gold who in 1948 concluded there must be amplification in the cochlea

In his own words:

"It dawned on me that the answer (to the problem of energy loss) *was that the body would have invented positive feedback. It just came to me in a flash - that nature is always so clever that, if there was a way out of that dilemma, then that's what it is going to be".*

Gold explained his ideas to von Bekesy but neither he nor any other auditory researcher took Gold's ideas seriously. Some thought that Gold's proposal would mean that sounds would emerge continuously from the ear - a ludicrous suggestion and demonstrably untrue - so people thought. Gold defended his ideas saying that sounds would only emerge spontaneously from ears which were defective or out of adjustment. He tried to find such spontaneous emissions from ears with tinnitus, by sealing a microphone to the ear canal, but his attempts failed.



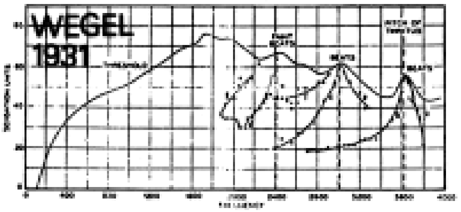
This positive feedback radio circuit gave Gold the idea that nature must have invented something similar

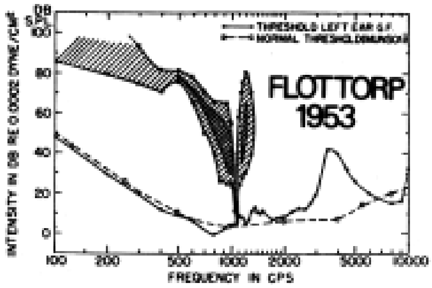
After his theory of hearing was rejected, Gold drifted away from the auditory field and enjoyed a very distinguished career in cosmology and geophysics. For 30 years auditory researchers hunted for the illusive 'second filter' and Gold's ideas were forgotten. But there were clues already in the literature.

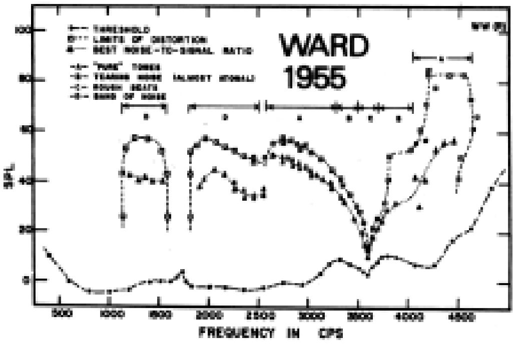
Early radios used positive feedback to increase sensitivity and frequency selectivity. They needed constant adjustment

First clues that the cochlea held a secret

For centuries those with a musical ear had been puzzled by hearing discordant sounds or 'aural combination tones' when two pure musical tones were played. Physiologists explained the effect as non-linear distortions between two contrasting signals passing along the same nerve pathway. But in 1931 Wegel reported such distortions with only one tone presented. Flottorp and Ward also reported hearing mysterious tones in their ears which reacted in a very frequency specific way with externally applied tones.



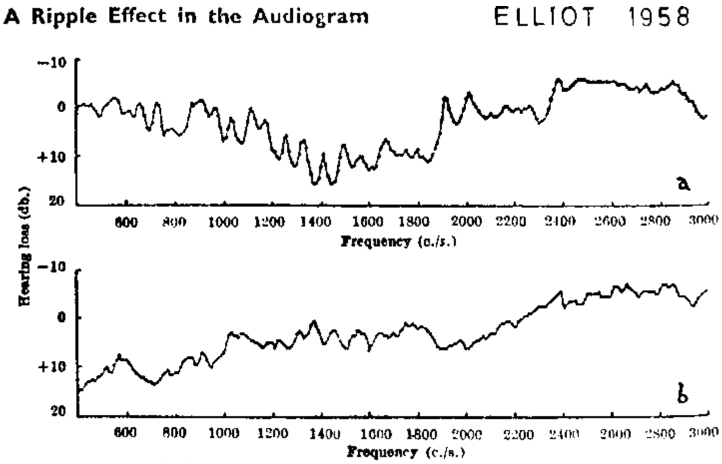




Before OAEs were discovered, several researchers reported strange noises in their ear when listening to pure tones as specific frequencies and levels or for a short time when the applied tone was removed

In 1958 Elliot, who was working to refine the definition of normal audiometric threshold, found very frequency specific 'ripples' which he could not explain - and which potentially limited the accuracy with which audiometrics could be conducted. Van den Brink also explored these ripples and found they were mirrored in loudness and pitch ripples too.

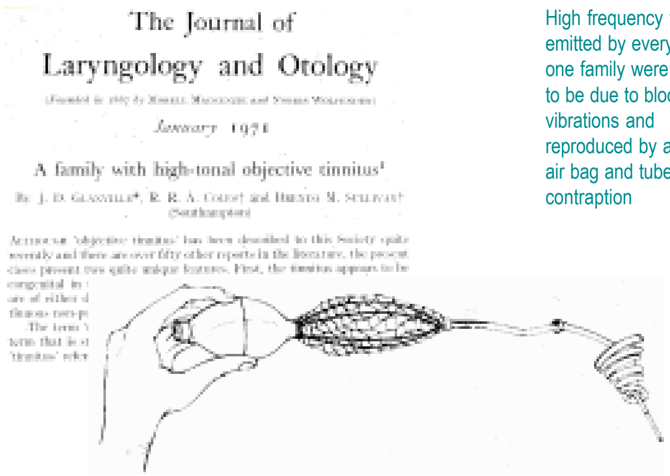
Elliot's high resolution audiograms showing ripples which could not be explained acoustically


A Ripple Effect in the Audiogram

ELLIOT 1958

Audiograms (*a*) for subject *A*, aged 21, and (*b*) for subject *B*, aged 28 years

Another incredible observation was made by Glanville, Coles and Sullivan in 1971. A whole family was found to emit continuous high pitched tones from their ears. The only explanation offered at the time was that some strange distortion of a blood vessel was causing the vessel to vibrate and 'sing'. No-one remembered Gold's cochlear amplifier suggestion of 1948.


The Journal of

Laryngology and Otology

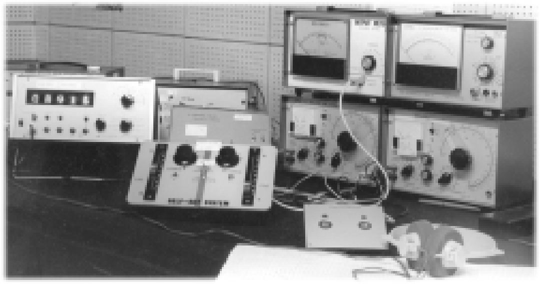
January 1971

A family with high-tonal objective tinnitus¹

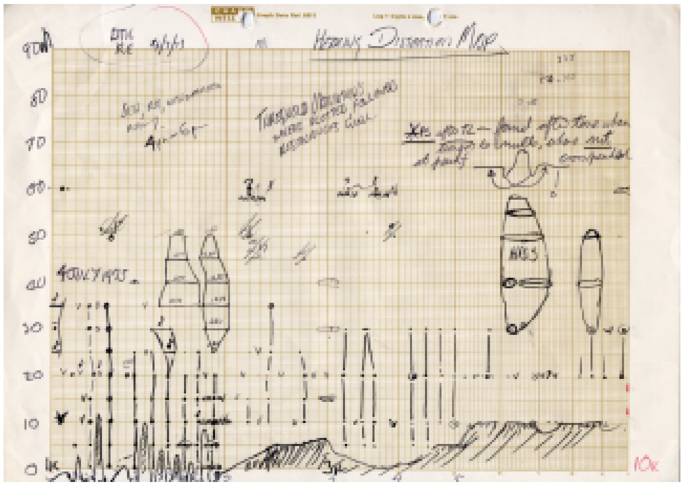
High frequency tones emitted by everyone in one family were thought to be due to blood flow vibrations and reproduced by a bellows air bag and tube contraption

Completing the puzzle

The strange ripples and distortions in hearing were intriguing. "I began charting them in great detail. Three dimensional charts of loudness enhancement, frequency intensity maps of loudness peaks and internal distortion areas. At almost regular intervals of frequency (every 100 to 300Hz) the hearing of healthy ears reached peaks of sensitivity and loudness. Pure tones sounded purer and louder at these frequencies. At the very strongest of these 'enhancements' sometimes a tone seemed to be audible even when no tone was applied. When a tone was applied a little higher or lower in frequency than the 'internal' tone, it battled with the weak external tone causing beats and 'roughness'. Was the internal tone really a vibration (albeit inaudible most of the time) or was it just a neural phantom? If it was a phantom tone then why were beats heard? Only real vibrations produce beats with an applied tone. And if the internal tone *was* real, that would explain why Wegel and Ward had heard aural combination tones when applying only one stimulus tone. And maybe the aural combination tone was a real vibration too.



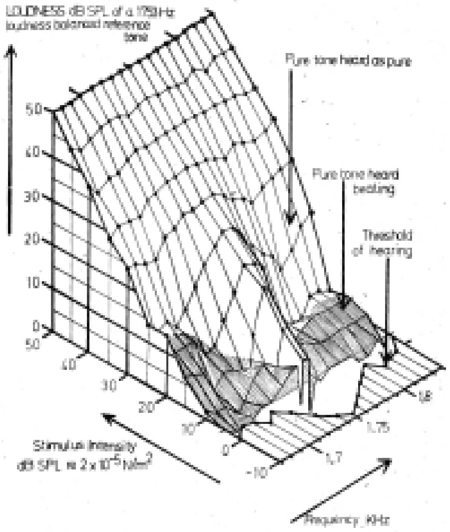
Kemp's psychoacoustic laboratory at the Royal National Throat Nose and Ear Hospital, London in 1975. Precisely calibrated oscillators delivered measured sound levels to ear via headphones. The listener manually adjusted level and frequency to map their auditory anomalies



An intensity frequency map of loudness enhancements and distortions heard by one listener during pure tone stimulation

"How could the matter be resolved experimentally? Bekesy had emphasised that the cochlear travelling waves always moved from the base to the apex of the cochlea wherever the external stimulation was applied, so a transmission of these sounds out of the ear seemed out of the question. But surely *internal* excitation would be able to drive the travelling wave in reverse and allow them to escape through the middle ear. So if there really where oscillations generated inside the cochlea they should be detectable in the ear canal.

"Bekesy had also taught, and all subsequent laboratory research confirmed that wave motion inside the cochlea was strongly damped - so how could sustained oscillations develop inside the cochlea. But if internal oscillations did exist then the cochlea must have low damping. And if it had low damping - low energy absorption - then internally generated waves could not only escape to the middle ear, but would be able to reverberate inside the cochlea, producing standing waves much as in an echoing room on a larger acoustic scale. Was this the explanation of the periodic enhancement of threshold and loudness seen by Elliot? If so then the input impedance of the ear should also show the same ripples."

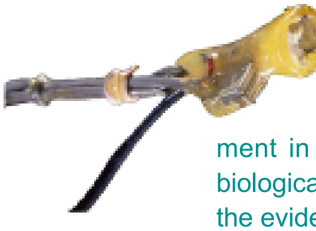


Loudness can be enhanced by more than 10dB near threshold at specific frequencies

The consequences for auditory theory of there actually being low damping and self sustaining oscillation in the cochlea were immense. From 1975 to 1977, psychoacoustic observations provided increasing support for this alarming hypothesis and only then did the idea of directly testing it emerge. As Gold had done back in 1948, it was time to listen in on the ear, but this time not an ear affected by tinnitus, but a normal healthy ear.

Crucial experiments - the discovery

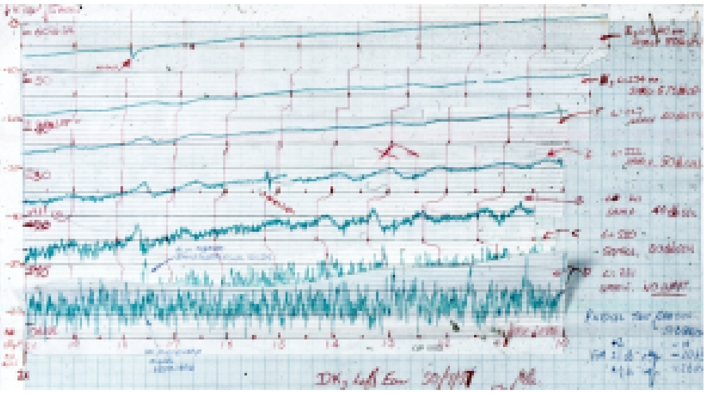
Kemp's acoustic emission laboratory at the Royal National Throat Nose and Ear Hospital, London, in 1977



The first OAE probes were assembled from hearing aid parts and epoxy resin

In July of 1977 the crucial experiment was performed. "I placed a miniature microphone salvaged from a hearing aid over the opening of my ear canal and then closed the ear canal with silicone putty to keep the ear's sound 'in'. I fed the output of the microphone into a hetrodyne analyser - an instrument which allows you to tune in to a very narrow frequency band (10Hz) at any frequency. Via a headphone I then applied a single pure tone at a frequency and level that I knew would give rise to a clear aural distortion tone as the external tone combined with the (supposedly) internal oscillation. I knew the frequency of the combination tone exactly by applying the formulate 2f1-f2 to the external tone (f1) and the internal tone (f2) and I accurately tuned the analyser to this frequency. Immediately there was a reading on the dial! As I changed the frequency of the external tone, the frequency of the combination tone in the ear canal changed exactly as the formula predicted. The internal tone was therefore physically present - not a neural phantom - and so should it also be detectable. I turned off the stimulus tone and tuned the analyser to the frequency of the supposed internal tone. It was there. A signal of 85dBSPL at 1253Hz was continuously present in my left ear canal. And another at 1760Hz. What's more, they were still there the next day at exactly the same frequency - within 1 or 2Hz". Such stability was difficult to obtain even with high quality electronic equipment in those days - and to find it in a biological system was hard to believe. But the evidence was incontrovertible.

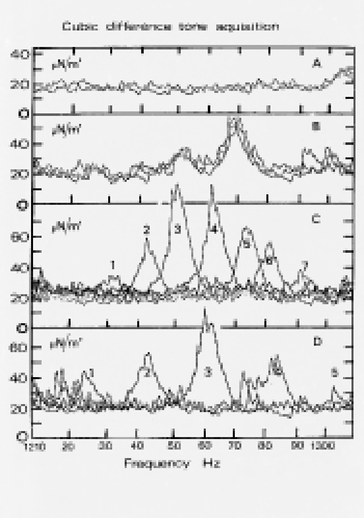
It was time to formally record the phenomenon. The manually controlled analyser was quickly converted into an audio frequency 'scanner' by attaching a slow electric motor. Fortunately the analyser also produced a pure tone output signal at the frequency to which it was tuned and this was used to stimulate the ear canal. An ear canal 'probe' was made consisting of a miniature loudspeaker and microphone so that the sound in the ear canal could be monitored as the stimulus frequency was swept up in frequency. Finally, the voltage driving the level meter of the analyser was fed to a chart recorder.



Measurement of ear canal sound level during sweep frequency pure tone stimulation at multiple levels showed ripples and provided the first recorded evidence of acoustic emission from the human ear, in July 1977

The results of the first acoustic scans reproduced the ripples measured psychoacoustically. And the higher the level of stimulation, the shallower the ripples in the ear canal became, just as the periodic loudness enhancements became insignificant for higher stimulus levels.

Finally, aural distortion products were successfully recorded. A distortion product of known frequency could be 'engineered' without reliance on the internal cochlear tone. When a pair of tonal stimuli less than half an octave apart are applied, the combination tone 2f1-f2 could be heard and was recordable in the ear canal as the scanner passed through the calculated frequency. Quite low levels of stimulation (30-40dBSPL) were used and the DPOAE was only detectable when its frequency was near to that of a loudness enhancement.



The first recording of a 2f1-f2 distortion product, July 1977. A is the noise floor, B is the spontaneous acoustic activity in the ear canal. C and D distortion products emerging with various applied tone pairs

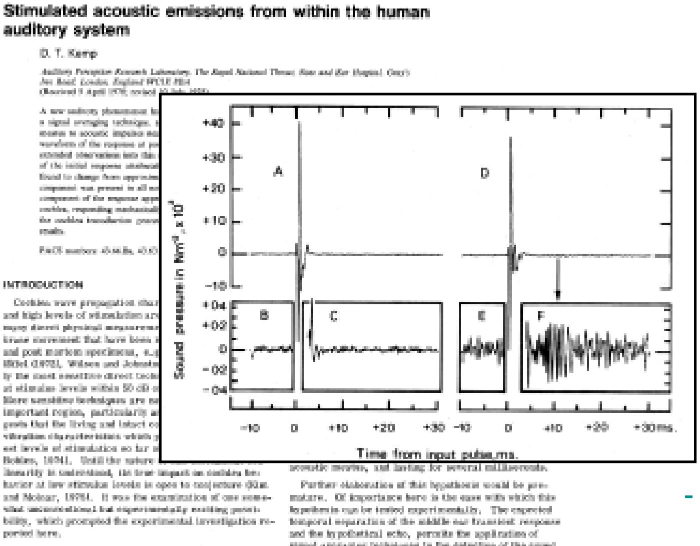
A new auditory evoked response

Within a few days in July 1977 it was clear that the obscure psychophysical 'ripple' phenomena called 'auditory microstructure' which had been known about for decades, were actually the tell-tale signs that, at least at low stimulus levels, the cochlea did not behave as Bekesy had taught and as everyone believed. In the absence of stimulation the healthy cochlea seemed to be on the brink of oscillation - of instability. As pioneer radio engineers had discovered, that state is the most sensitive state for any receiving apparatus to be in. When weak acoustic stimulation was applied there seemed to be little or no damping to prevent the cochlear travelling wave reverberating inside the cochlea. The new acoustic evidence suggested that in the healthy ear the travelling wave reflected back and forward between the middle ear and a place inside the cochlea for hundredths of a second, instead of dying away inside the cochlea in a few thousandths of a second as Bekesy had observed in the cadaver. And at a few special frequencies the cochlea supported self-sustained oscillations, with laser-like frequency precision. This strongly supported the idea of a biological amplifier action just as Gold had proposed in 1948. And yet, when every-day levels of stimulation were applied the self oscillation stopped and the periodic loudness enhancements faded away. Cochlear behaviour was therefore level-dependant (i.e. mechanically non-linear) just as Rhode had demonstrated in the squirrel monkey in 1970. Mechanical nonlinearity in the cochlea had been vigorously disputed by the auditory research community, even though neural data also suggested that nonlinear distortion products were present in basilar membrane motion. But they were wrong.

In 1977, it seemed that, as in 1948, the true significance of these experiments for auditory science might be lost due to entrenched thinking and misunderstandings about the highly technical acoustic experiments. To help overcome this, one final experiment was performed. The reasoning was that if sound energy reverberated inside the cochlea as it did in a large room, then applying a short click to the ear would, like a clap in a room, resulting an echo. The hetrodyne analyser was replaced by a physiological signal averager and the pure tone stimulus was replaced with a click. Sure enough, the ear gave an 'evoked response' to the click - a long complex emission of sound lasting 16 milliseconds and more. It was like nothing seen before from the auditory system. It was a 'cochlear echo'.

The first click evoked acoustic emission (TEOAE). The repeatability of the complex response is evident. Traces (counting from the top) 2 and 3 from the right ear 4, 5, and 6 from the left.

Following the publication of the first reports of stimulated acoustic emissions, in 1978 several workers quickly reproduced the findings notably Rutten, Wit, Ritsma and Wilson.

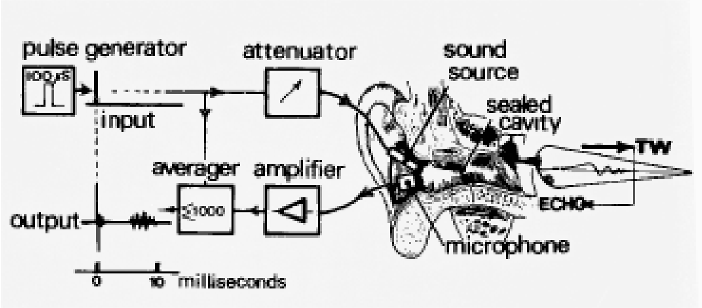


Stimulated acoustic emissions from within the human auditory system

D. T. Kemp

INTRODUCTION

The first paper on OAEs, published in the Journal of the Acoustical Societyof America



Schematic of the experiment to present the new cochlear behaviour as an evoked response

The first OAE instruments

The success of the click evoked acoustic response experiment demonstrated how easily the technique could be applied to hearing testing. A portable TEOAE instrument called the 'Cochlear Sounder' was built for the lab by Rudolph Chum early in 1978. It used an electronic delay line and recirculated data to create a rolling 3-4 second averager which could continuously display the response waveform on a small oscilloscope. Like modern TEOAE instruments, it used time gating to cut out the stimulus and presented multiple click levels to demonstrate non-linearity.

Rudolph Chum who constructed the Cochlear Sounder in 1978

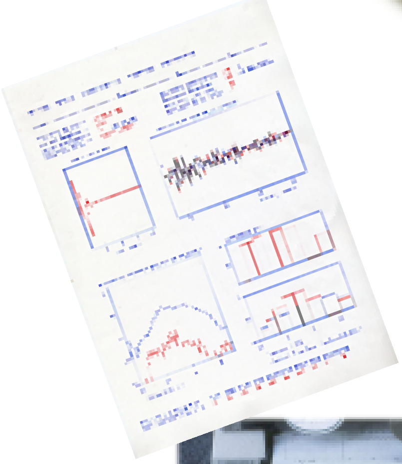
Early in 1978 the general method of using sound emission from the ear as a hearing screening test was patented for the Royal National Throat Nose and Ear Hospital in Europe and in the USA by the National Research and Development Council (NRDC), a State body. From 1978, the Cochlear Sounder was demonstrated to all the major manufacturers of the time, including G.S.I. and Madsen. However, few audiologists and no instrument companies understood the significance and potential of OAEs at that time. It was 1984 before a long standing British audiometric instrument manufacturer, Alfred Peters Ltd., committed itself to investing in the manufacture of the first commercial OAE instrument.

The portable Cochlear Sounder, the world's first OAE instrument operational in 1978 and demonstrated to leading audiometric instrument manufacturers of the time

OAE research and the task of developing OAE measurement procedures continued at the ILO through the 1980s, mostly using the a laboratory OAE system built around the SLAM mini computer.

Alfred Peters Ltd. incorporated the OAE procedures developed at the ILO into the AP200 Otoacoustic Emission Processor, which they launched in 1985.

From 1981 the ILO laboratory OAE system was based on the 'SLAM' computer made by C.E.D. Ltd. The data analysis and presentation used on both the Peters AP200 (below) and ILO88 clinical OAE systems was developed on the 'SLAM'.



The first commercial OAE instrument, the Peters AP200

This AP200 was not commercially successful and only seven were sold before the Company folded. Although the instrument had noise artefact rejection and spectrum analysis, the probe was poorly designed and the user had no effective means of checking the probe fit while testing and no data display. The process of collecting, validating and plotting the test results took some five minutes and only then would it be discovered if the recording was successful.

The AP200 OAE probe

With a continuing lack of interest by most of the established audiological instrument manufacturers and the failure of the only commercial OAE instrument, the development of applications for OAEs depended totally on academic laboratory efforts. John Stevens at Sheffield in the UK, Mark Lutman at Nottingham, UK, and Neils Johnsen in Hellerup, Denmark, each developed their own TEOAE system for evaluation in newborn hearing screening. In the USA, Brenda Lonsbury Martin and team designed a clinical DPOAE instrument based on exhaustive laboratory tests.

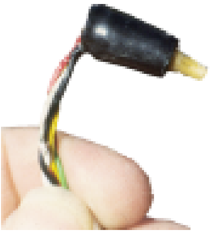

Peter Bray, co-designer of the ILO88

In 1987, in England, two personal computer based TEOAE instruments were being developed for use outside of the laboratory.

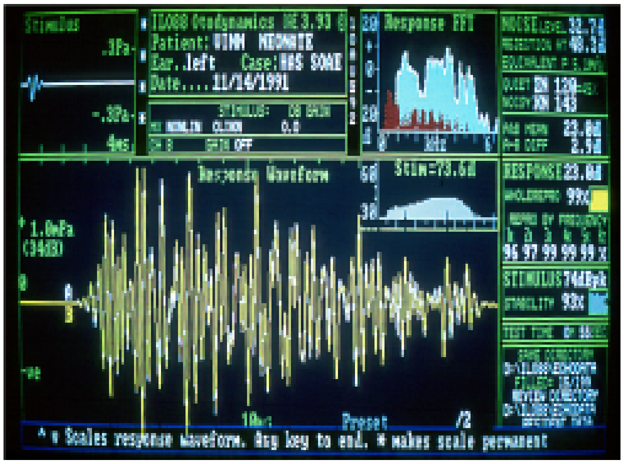
At the Institute of Laryngology and Otology (ILO) London, Peter Bray developed the 'ILO88' in Kemp's laboratory, based on the IBM PC. The design of the instrument, consisting of two PC expansion cards and a separate amplifier. This was suited to duplication and use in other laboratories.


Siobhan Ryan with the prototype ILO88 in 1987

Siobhan Ryan performed the first newborn screen with the ILO88 and found that a 20dB reduction in probe stimulus drive was needed due to the small size of newborns' ear canals.


The original neonate probe designed in 1988 for the ILO88

The ILO88 featured advanced analytical software, which provided real-time monitoring and fast frequency analysis. Real-time audio FFT processing was just only feasible with PCs at that time and had not previously been used in audiometric assessment. Central to the ILO88 philosophy was repeated monitoring of the ear canal stimulus waveform to detect probe movement and poor fitting was continually monitored. Noise contamination was measured by subtracting pairs of averaged responses and data quality was summarized by a 'reproducibility' parameter derived from cross correlation. All test conditions were saved.



^ v Scales response waveform. Any key to end. * makes scale permanent

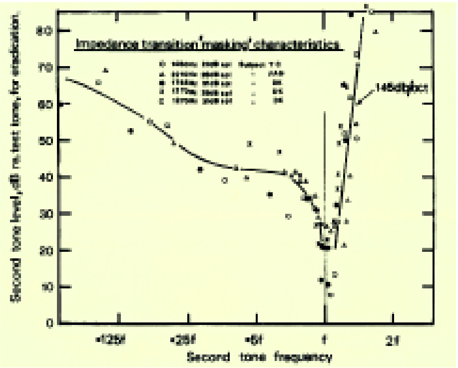
The ILO88 screen evolved rapidly from 1987, to give operators extensive feedback on test conditions and results

In 1988, the MRC Institute of Hearing Research Nottingham introduced its 'POEMS' OAE instrument, using the BBC computer. Based on their own OAE research it was a TEOAE instrument, initially with a waveform-only display. It went into service in at-risk newborn screening programmes in St. George's Hospital London and several other hospitals in the UK.


The MRC POEMS used a personal computer to process signals and display TEOAE waveform data in 1988

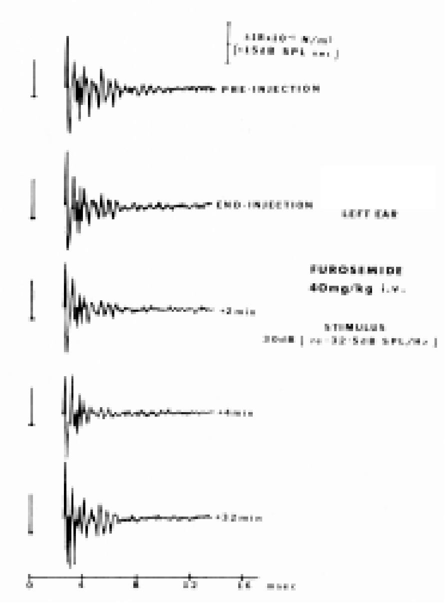
OAE science: the early years

Well before the application of OAEs to screening and clinical diagnostics, OAEs were studied in the laboratory. A whole series of questions had to be answered before the relationship of OAEs and hearing could be understood. The initial series of experiments in 1977 (reported by Kemp 1978) had demonstrated that OAEs were absent in ears with hearing loss. They were nonlinear phenomena with substantial delays - not unlike that expected from a reversal of the cochlear travelling wave. It had also been demonstrated that OAEs evoked by single tones could be suppressed by applying a second stronger tone. This suppression was found to be very frequency specific with a tuning curve as sharp as that of hearing.



Stimulus frequency OAE suppression tuning curve obtained in 1977 demonstrated the close association between OAEs and the cochlear hearing mechanism

The first scientific presentation of acoustic emissions was in April 1978 at a meeting of the British Society of Audiology in Keele University. The new discovery was received with great skepticism, not least because the concept of waves travelling in reverse in the cochlea contradicted firmly held views at the time.



From Anderson and Kemp 1979. The well known reversible effects of the loop diuretic Furosimide on hearing were mirrored in the reduction of TEOAEs for 30 minutes after IV injection

Many physiologists also doubted the early evidence that OAEs came from the cochlea. In 1978-9 Evans and Wilson at Keele tested the possibility that OAEs came from muscle reflex spasms but found OAEs in the absence of an active middle ear muscle. To convince other scientists to conduct research into OAEs it became necessary to demonstrate that OAEs were depressed as hearing threshold was raised, either by noise induced temporary threshold shift or reversible ototoxic drugs.

Stewart Anderson joined Kemp to perform experiments, which fully confirmed a close relationship between OAEs and hearing.

Stuart Anderson, who took part in the initial laboratory validation of OAEs at the ILO in 1978-81

The first international airing of the new concepts of cochlear function occurred in September 1978 at the Inner Ear Biology Workshop in Seefeld, Austria. Many researchers realised the significance of the findings, including Egbert deBoer and Duck On Kim. Kim was already working on cochlear mechanical nonlinearity in St. Louis, using neural techniques. After the Seefeld meeting, he quickly adapted the otoacoustic emission method for animal laboratory use and obtained clear DPOAEs from rodents. He was also the first to observe suppression of DPOAEs due to electrical stimulation of the cochlear efferent system in 1979.

NON LINEAR & ACTIVE
MECHANICAL PROCESSES
IN THE
COCHLEA

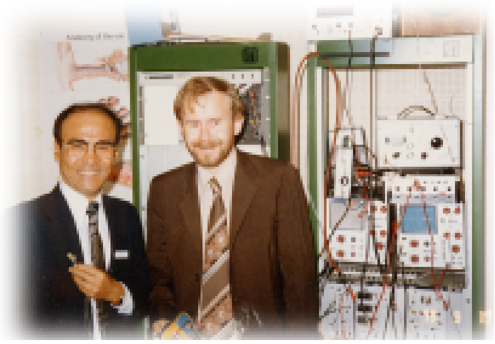
SYMPOSIUM
NON-LINEAR and ACTIVE
MECHANICAL PROCESSES
IN THE COCHLEA

PROGRAMME

SEPTEMBER
1979
THE INSTITUTE OF LARYNGOLOGY AND OTOLOGY
BRITISH POSTGRADUATE MEDICAL FEDERATION
UNIVERSITY OF LONDON

In September 1979, the first international meeting was held to discuss the implications of otoacoustic emissions for hearing theory. The symposium on 'Nonlinear and Active Mechanical Processes in the Cochlea' was held at the ILO, London and organized by Kemp and Anderson. At this time mammalian hair cell electro-motility was not known, although at the meeting Fettiplace and Crawford had reported electro-resonance of amphibian hair cells in which kinocilial motility was involved. It was known that the stereo cilia of mammalian sensory cells were mechanically nonlinear for large displacements but the majority present did not believe this nonlinearity would be transmitted to basilar membrane motion. The idea that the hair cell receptor potential could generate a force to affect basilar membrane mechanics (bidirectional transduction) was vigorously disputed.

This was despite an important new observation of mechanical nonlinearity on the basilar membrane presented to the meeting by LePage and Johnstone. Most felt that otoacoustic emissions were a fortuitous by-product of cochlear function, an epiphenomenon, and that OAEs had no important message for cochlear physiologists. Nevertheless, from that time in 1979 the term 'active process' came to be used to indicate the as yet unknown mechanism that turned the linear, highly damped and poorly tuned mechanics of the basilar membrane seen be Bekesy into the nonlinear, lightly damped and sharply tuned basilar membrane evidenced by OAEs. The proceedings of the meeting are published as Vol. 2 of Hearing Research 1980, No. 3/4.



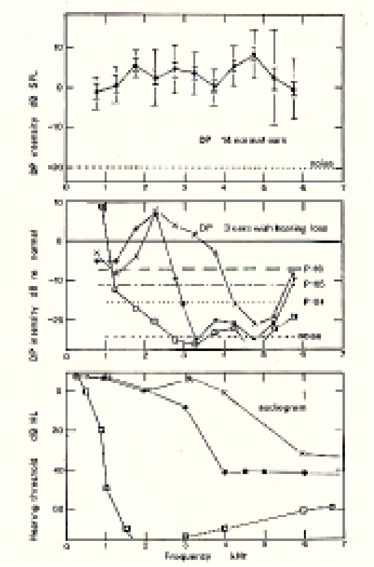
Dr Kemp in his laboratory with Dr Tanaka during the 1979 symposium

Early studies of Distortion Product OAEs

Although DPOAEs were recorded in the first week of observations in July 1977, they were initially overshadowed as a clinical method by the technical simplicity of TEOAE measurements and by the conceptual simplicity of making stimulus frequency observations. DPOAEs seemed difficult to record in human ears, required two independent stimuli delivered by separate probe transducers and a very high quality analyser. It was Kim in St. Louis who discovered how strong and readily recordable DPOAEs were in laboratory animals. His observations triggered DPOAE research in a number of laboratories in the USA, including that of Lonsbury and Martin who explored the phenomena in rabbits together with Probst.

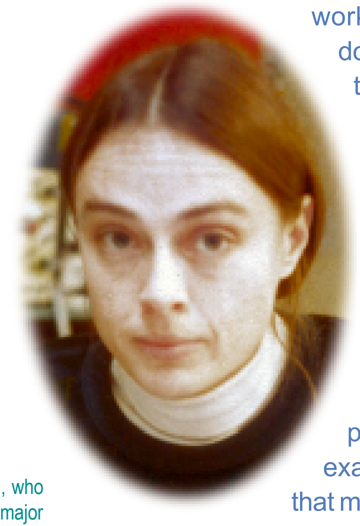
Clinical applications of DPOAEs were first explored 1984 in London at the ILO using a swept frequency DP tracking analyser. Unlike modern instruments, complex data from rapid 2s sweeps of the whole frequency range were made with stimuli f1,f2 at a fixed ratio, and averaged. The DPOAE intensity fell sharply at frequencies where the audiometric threshold of the subject was above 30dBHL. Work in other centres, notably by Harris and Probst, strengthened the evidence linking the loss of DPOAE and TEOAE with threshold elevation.

Laboratory studies on human DPOAEs showed that they possessed an inherent latency similar to TEOAEs. They could be suppressed by an additional stimulus tone and suppression tuning curves showed sharp tips. However it was clear that DP generation was complex with more than one source. DPOAEs obtained with close stimuli exhibited a different latency to those with widely spaced stimuli leading to the Wave and Placed hypothesis (Kemp 86).



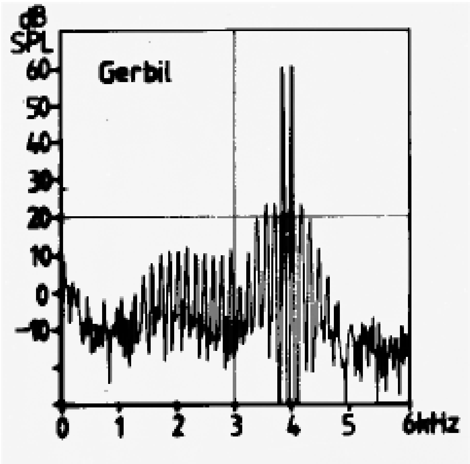
DP cochleography. The first DP-grams showing good correlation with the audiogram of impaired ears, 1984

Until the advent of more powerful computer based systems around 1990, most DPOAE studies were conducted on rodents where the signals were relatively much stronger than humans. Pioneering work on DPOAEs was done by Ann Brown at the ILO from 1982. In a series of experiments suppression tuning curves were explored, the effects of noise and ototoxic drugs investigated and the relationship to the cochlear microphonic was examined. It was found that most suppression was usually but not always obtained with a masker near to the f2 frequency, implying that DPOAEs most often gave information about the hearing mechanism at f2, rather than at the frequency of the DP. Distortion Products in the cochlear microphonic were found to be so similar to DPOAEs that they could only have been generated as the DPOAE wave stimulated the base of the cochlea.



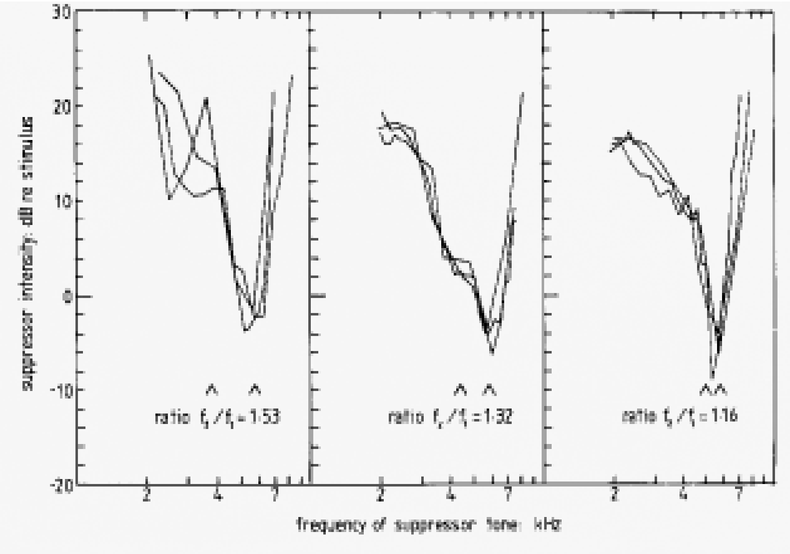
Ann Brown PhD, who undertook a major laboratory study of DPOAEs at the ILO from 1982

From these experiments emerged the first understandings of how to control the stimulus parameters for optimum acquisition of DPOAEs. For maximum 2f1-f2 DPOAE The ratio of f1 to f2 should be around 1.2-1.3, and as the level of f2 was lowered to create a more sensitive measure of cochlear status, the level of f1 needed to be lowered by a much smaller amount. It's now accepted that this is a result of the sharpening of the travelling wave envelope at lower levels.



Two close stimulus tones at 60dBSPL can result in more than 20 DPOAEs (from Kemp and Brown 1986)

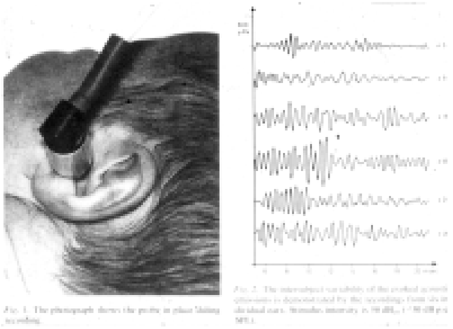
Ann Brown's work also revealed that many DP components could be produced simultaneously, emphasing that the underlying nonlinearity in the cochlea was quite severe. This observation also stands as a caution that modern DPOAE instruments which record only 2f1-f2 are not utilising all the information available.



DP suppression tuning curves obtained repeatedly from a gerbil at three different stimulus frequency ratios from Brown and Kemp 1984 . The sharp tips at f2 help demonstrate that DPOAEs convey information about cochlear status for frequencies near f2.

First applications for universal newborn screening

In 1983, Niels Johnsen, working at the Gentofte University Hospital, Hellerup, Denmark, applied TEOAE to healthy newborn infants for the first time using a machine built at the hospital. He had complete success and suggested it as a method of infant screening. The idea of newborn screening with OAEs was taken up in France by Pujol and Uziel (Montepellier) from ~1986. Using their own instrument they confirmed the potential of OAEs and enthusiastically promoted its use in screening.



Niels Johnsen reported the first recordings of OAEs in newborns in 1983

From 1988 the British ILO88 began to be applied to newborn hearing screening with some success. Under Dr. Peter Watkin the ILO88 went into service at Whipps Cross Hospital, London, which became the first hospital in the world to offer routine well-baby newborn hearing screening with OAEs.

Dr Peter Watkin pioneered routine UNHS with OAEs in London from 1989

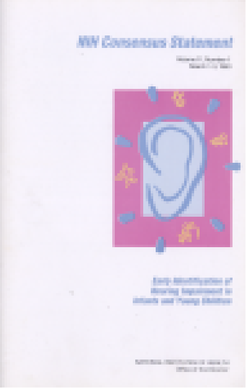
In 1989, the US Department of Maternal and Child Health funded a feasibility study of universal newborn screening at the Women and Infants Hospital, Providence, Rhode Island, under paediatrician Dr. Betty Vohr, with scientific director Karl White PhD.

Dr Betty Vohr supervises the screening of a newborn with the ILO88 in 1989

The first UNHS team receive training on the ILO88 OAE instrument in 1989

After trials of OAEs against the ABR instruments available at that time, they selected the ILO88 TEOAE instrument for the study, mainly on the grounds of speed and economy.

The Rhode Island Hearing Assessment Project study proved successful and in 1993 an NIH Consensus Statement recommended universal newborn hearing screening with TEOAE favoured as the initial screen.



NIH Consensus Statement 1993 recommending universal newborn screening with OAEs accepted as the first screen

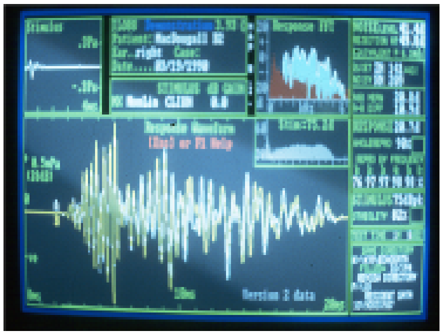
Other important scientifically controlled studies of OAEs in newborn hearing screening began around this time. The Wessex Hearing Screening Project in the UK under Dr. Colin Kennedy and Lindsay Kimm rotated an OAE screen (using ILO88) around several districts. They proved a significant increase in the rate of detection of infant hearing loss with UNHS compared to traditional 8m behavioural testing. In the USA, the NIDCD Multi–Center Screening Methods project compared the effectiveness of TEOAEs, DPOAEs and ABR and found them equally effective at detecting infant hearing loss when optimal stimulation and pass criteria for each type of test were applied.

Lindsay Kimm, manager of the UK's Wessex Hearing Screening Project

Susan Norton PhD, leader of the NIDCD multi-center trial

The development of OAE instruments and applications

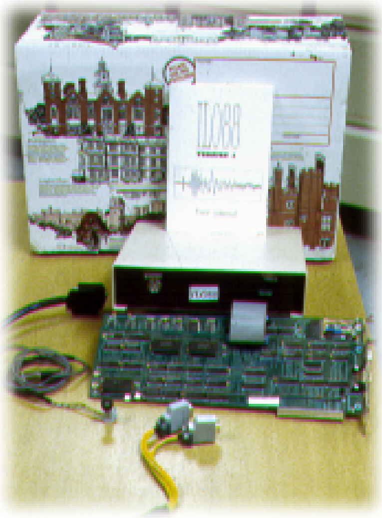
The reluctance of manufacturers to invest in OAE technology throughout the 1980s and the collapse of the only interested commercial company, Peters Ltd., in 1987 held back the development of clinical OAE instrumentation. Ten years after the first demonstration of the 'Cochlear Sounder' to the industry there seemed to be no way that the increasing need for a robust and effective OAE system for clinical research could be met.



ILO software

In 1988 the Kemp family decided to purchase the OAE patent rights from the British Government technology transfer agency and gained permission from the Institute of Laryngology and Otology, University of London, to manufacture and sell the 'ILO88' commercially in return for royalties to support hearing research at the ILO and RNTNE Hospital.

The company **Otodynamics Ltd.** was formed, offering the ILO88 system by mail order for self installation in IBM compatible PCs. The kit comprised two large PC expansion cards, a mains powered amplifier, probes and rudimentary instruction manual. A key feature of the software was the rich realtime feedback of information to the operator. The ILO88 gained FDA clearance for sale in the USA in 1989 with the assistance of Janice Painter of GSI. However, distribution negotiations broke down and Otodynamics began marketing directly in the USA.



The ILO88 kit available by mail order from Otodynamics in 1988

The ILO88 kit configured with an early laptop computer as sold in 1989

In Japan, the ILO88 was offered for research purposes with an early laptop computer.

Otodynamics Ltd. was a high risk venture for the Kemp family but very soon academic hospitals and auditory research laboratories around the world were placing orders for the ILO88 kit. The company was a success and won a British national award for export achievement in 1993. The ILO88 became the gold standard for TEOAE measurements. The ILO88 was adopted for the Rhode Island newborn hearing screening trials and the screening application stimulated the development of a new neonatal OAE probe.

Otodynamics' neonate probe developed 1990-3

Many research laboratories needed DPOAE facilities and the ILO88 could not be expanded. Both Otodynamics and The Virtual Corporation launched a DPOAE instrument in 1992. The Virtual 330 was a DPOAE-only instrument, based on the Lonsbury-Martin laboratory DPOAE research and interfacing with an Apple Mac. There were high expectations at this time that DPOAE technology could deliver an objective audiogram, which was never claimed for TEOAE.

The Virtual 330 DPOAE instrument launched in 1991

Otodynamics launched the ILO92, which was the first OAE instrument to offer both TEOAE, DPOAE and SOAE measurement facilities. With its advanced analytical software it became a widely used tool for laboratory and clinical research.


The Otodynamics ILO92 Otoacoustic Analyser performed TE and DPOAEs and was launched in 1992

By 1994 the success of OAE screening applications was clear to all and most audiological instrument manufacturers made plans to offer a clinical OAE instrument. Madsen launched the Celesta DPOAE machine at the time.

However, a special need for portability was developing in newborn screening applications. In 1993 Otodynamics addressed this need by introducing a battery powered instrument which linked to any IBM compatible PC via the printer port. The Echoport designed by Peter Bray was ideally suited for use with laptops. Its laptop format became the model for later products released by GSI (60) and Madsen (Capella).

The world's first battery portable OAE instrument, the Otodynamics ILO88 Echoport, designed by Peter Bray

The first standalone OAE screener, the Otodynamics Echosensor, launched in 1993

In 1993, Otodynamics also launched the world's first standalone OAE screener, the Echosensor, designed by David Brass. This unit was battery powered, required no computer and displayed OAE intensity directly. It was mainly marketed in Europe.

The need for simplicity and extreme portability in universal screening programmes intensified. Several hand-held OAE screeners were introduced from 1997. These included the Otodynamics Echocheck, the Fischer Zoth Echoscreen and the Biologic AuDX.


David Brass PHD engineered the Echosensor and Echocheck screeners

The Echocheck used traditional averaging techniques to assess the signal to noise and intensity of TEOAEs. The Echoscreen did not measure OAE intensity but employed a binomial probability assessment related to the FSP technique used in early ABR systems. Like ABR screening, neither device provided frequency specific information. The Biologic AuDX was a DPOAE device which scanned a number of frequencies. It was joined in the market by other instruments, including the Etymotic Eroscan, also a DPOAE instrument. Subsequently TEOAE options were added to both these DPOAE instruments.


Otodynamics Echocheck TEOAE hand-held screener


Fischer-Zoth Echocscreen TEOAE screener

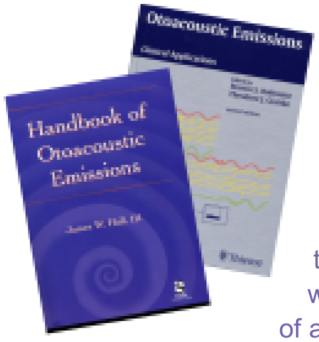
Not all screening services chose the simplicity of hand-held devices. In Europe, particularly in the UK national program, access to detailed OAE data and test history was felt to be desirable. This was for traceability and as a resource to improve future screening methodology. PC based analytical OAE instruments such as the Echoport continue to be used in screening for these reasons.


Biologic AuDX DPOAE screener


Etymotic Research Eroscan

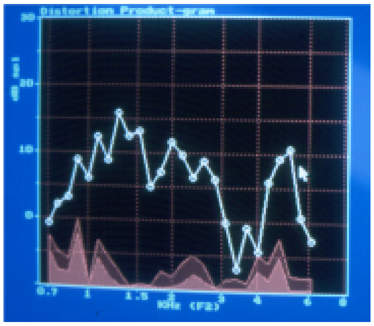
OAEs for diagnostic applications

The primary diagnostic application of clinical OAE instruments is the frequency specific assessment of the degree of cochlear involvement in hearing pathology. Hence, by comparison of left and right ear OAEs, sudden hearing loss can be categorised as most likely of cochlear origin or not, and the ongoing status can be monitored. The degree of damage to the cochlea in diagnosed 8th nerve tumours can be assessed using OAEs. With infants failing ABR screening, OAE can be used to confirm cochlear involvement, which is essential for the selection of appropriate amplification.

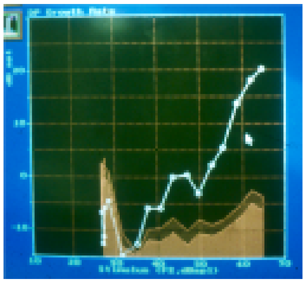


Handbook of Otoacoustic Emissions (Hall, Singular Press) and Otoacoustic Emissions - Clinical Applications (Robinette and Glattke, Thieme Press) provide a detailed introduction to the clinical uses of OAEs.

Routine diagnostic applications of OAEs stem from their use as part of the audiometric test battery. High quality measurements must be obtained over a wide range of stimulation conditions. DPOAE and TEOAE recordings complement each other. TEOAEs are considered to be most sensitive to mild departures from normality, and readily alert to over-activity. However, the method gives no information once threshold is elevated by 20-30dB and it is also not useful above 6kHz. DPOAEs complement TEOAEs in these respects. The standard DP clinical measurement consists of recording the DP component 2f1-f2 as a function of frequency. The DPOAE method works best from 2kHz upwards. Acoustic calibration difficulties begin to limit the reliability of measurements above 8kHz in human ears. By varying the stimulation level DP-grams can be made more or less sensitive to hearing loss. This is extremely useful for clinical investigations, allowing a broad assessment of the severity of cochlear pathology. The actual intensity of normal DPOAEs has a wide spread of intensity, with less than 50% correlation with hearing threshold. Tracing the growth of DP intensity with stimulus level backwards to define the onset of DP production has been popular. However, the DP thresholds obtained in this way are only about 60% correlated with audiometric threshold and so cannot replace the audiogram. OAE latency can be accurately measured with DPOAE but the clinical application of this is so far limited to testing the validity of DP responses. DPOAE intensity can be used to continuously monitor cochlear status which has obvious clinical applications.

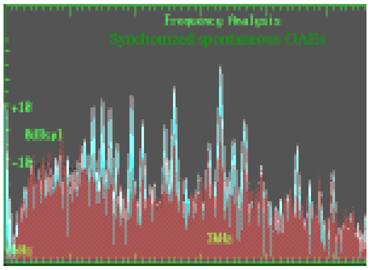


The DP-gram indicates cochlear activity as a function of frequency



By incrementing stimulus level with fixed frequencies, DPOAE growth function is obtained

Spontaneous OAEs can serve as an even more sensitive monitor of cochlear status - although less than half of normal ears exhibit these signals.



Spontaneous OAEs indicate over-amplification and feedback in the cochlea. Excessive activity (as below) can result in physiological tinnitus but this is normally associated with function

Several OAE instruments provide facilities to perform some if not all of the above functions. Otodynamics launched a battery portable clinical system - the ILO292 - in 1996, which has been continually updated. It performs TEOAE, DPOAE and SOAE functions, including ongoing DP monitoring. The Madsen Capella also offers comprehensive facilities with the addition of an optional middle ear analyser.

The Otodynamics ILO292 DP Echoport as originally launched in 1996 offered facilities for diagnostic OAE uses

The Madsen Capella DP, TE and SOAE instrument launched around 1999

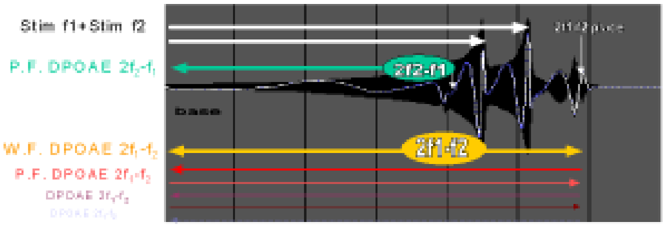
Advanced OAE techniques

The vast majority of OAE applications use the basic techniques of TEOAE, DP-gram and DP growth function pioneered in the 1980s and commercial instrumentation reflects this fact.

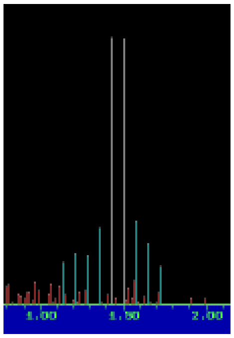
There have been several technical innovations aimed at improving the speed or efficiency of OAE measurements. 'Maximum Length Sequence' or MLS stimulation has been explored by MRC and the University of Southampton UK as means of speeding up TEOAE data collection. The new stimulus is effectively white noise, and so provides a stronger continuous stimulation rather than the infrequent clicks normally used for TEOAEs. The value of the MLS stimulus is that it yields responses which can be readily transformed back to click-equivalent responses. So far this has not proven to have major overall practical benefits but is valuable as a research technique. GSI introduced a technique of dual tone pair stimulation and analysis into their GSI 60 product to increase the speed of DPOAE acquisition. Although significant, the improvement is not dramatic. A DPOAE product by Vivosonic Inc moves away from 'traditional' frequency analysis techniques in order to allow more immediate monitoring of the DP signal. Such optimisation may have special applications in DPOAE monitoring and research.

Of more fundamental significance are attempts the increase the interpretability of OAE data. Two areas have been of concern. It has been known since the mid 80s that at least two sources of DPOAE transmit DPOAE to the ear canal - one from the place in the cochlear dealing with the stimulus frequency (f2) and one from the place dealing with the frequency of the DPOAE. This gives rise to interference and irregular structure of the DP-gram. It is well known that use of a carefully selected 3rd stimulus tone can suppress the DP place signal and smooth out these irregularities. The presumption is that the remaining DP will be more directly related to hearing status. Hortmann GmbH has introduced the EchoMaster instrument with this feature. However the central issue of how best to define hearing status with DPOAEs remains. Important research by Boerge has resulted in a way to optimise the relation of DP threshold to hearing threshold by changing the relative intensities of the two stimuli used to determine DPOAE growth with level. However, it seems unlikely that a very high correlation with audiometric threshold will be achieved - underlining the fact that OAEs are a measure of outer hair cell function and not of hearing.

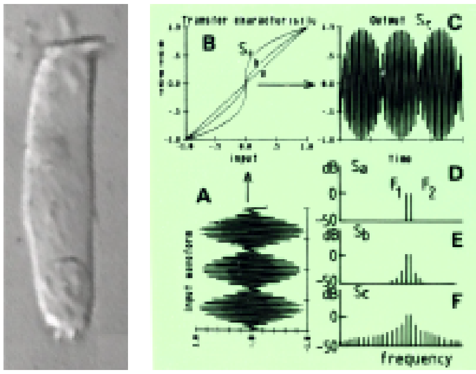
It has long been recognised that many distortion products emerge simultaneously. In addition to 2f1-f2, 3f1-2f2 and 2f2-f1 are often significant. Attempts to utilise the extra information these signals may contain have gone in two directions. Study of the complete pattern of distortion products enables models of outer hair cell non-linearity to be developed and tested. This may be important in the refinement of methods to assess and quantify hair cell status and efferent control status (see below). DP-grams constructed from components other than 2f1-f2, especially 2f2-f1, may compliment the standard DP-gram particularly near rapid changes in threshold.



DPs can arise from several places in the cochlea. Internal reflection and interference occurs



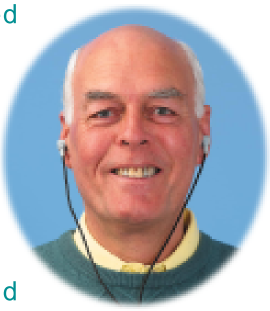
DPOAE spectrum showing multiple components



Nonlinear outer hair cell input output characteristics necessarily produce distortion products. The exact pattern of any nonlinearity $(B_{a,b,c})$ physically determines the particular pattern of distortion product (D,E,F)

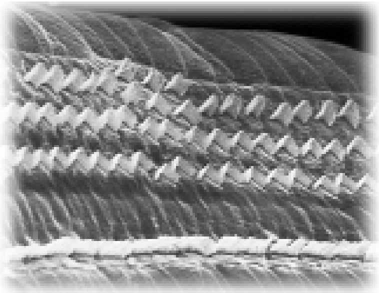
The development with the greatest potential clinical impact comes from the fact that OAEs can indicate binaural interaction and the operation of the cochlear efferent system. Although suspected through the 1980s, it was not until Collet demonstrated the suppression of TEOAEs by contralateral noise, in 1991, that clinical research began with this technique. The literature is extensive, with major contributions from Berlin, Collet, Hood and Tavartkiladze Many major questions remain - not least concerning the functional role of the cochlear efferent system. Nevertheless, we are on the brink of seeing OAEs used as a practical tool of neurological investigation of the auditory system.


The Otodynamics ILO292 USB-II, designed for binaural measurement of OAEs and capable of quantifying binaural interactions


Binaural interactions affect OAEs

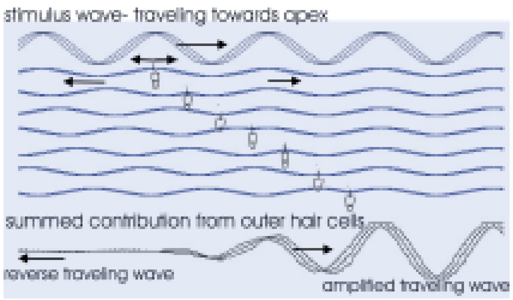
Understanding OAEs today

In 25 years many questions about OAEs have been answered and many problems concerning the cochlear resolved. Most would accept today that the primary function of the outer hair cell population of the organ of Corti is to sustain stimulation in the cochlea long enough for the basilar membrane to develop a strong frequency specific response. Their action is known as the 'cochlear amplifier' and it serves not only to increase hearing sensitivity and frequency discrimination, but also to provide the signal compression needed to match the enormous dynamic range of sounds to the limited dynamics range of nerve fibres.


The surface of the organ of Corti. Hairs of the inner hair cells (nearest row) detect fluid vibration causing the cell to activate the auditory nerves. Movement of the outer hair cells releases fresh mechanical vibration which replaces that lost to fluid viscosity

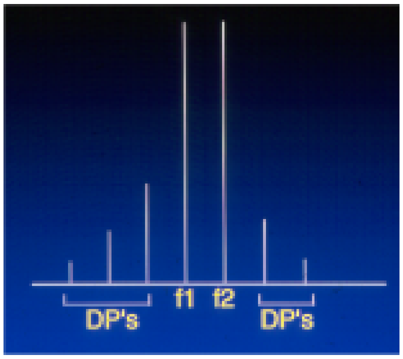
OAEs are definitely peripheral to this process. They are due to leakage of energy from the cochlea and ultimately must be regarded as due to imperfections in the cochlear system. Nevertheless, the intensity of OAE generally indicates the health of the cochlea. Therefore we should not see OAEs as a measure of imperfection but as a measure of how near the cochlea has come to reaching the limit of performance imposed by the very nature of biological tissue.

Outer hair cells are the driving force behind this remarkable feat. Un-damping of the basilar membrane is essential to overcome the loss of stimulus energy to friction. Each outer hair cell responds to create its own minute travelling wave, synchronised to the stimulating wave. Whereever it is located, its instantaneous contribution is guaranteed to support the stimulating wave - just as inside a laser. Equally their individual contributions to a reverse wave will annihilate each other - but ONLY so long as the distribution of their contribution is spatially uniform. In reality, as outer haircell gain is increased, there comes a point where any small irregularities in outer hair cell arrangement activity become magnified and significant stimulus frequency energy travels backward, to cause OAEs.



Each outer hair cell creates its own travelling wave along the basilar membrane, both forward and backward. The forward wave is strengthened (ie amplified) by this but the reverse contributions destroy each other, unless there is spatial irregularity in outer hair cell activity

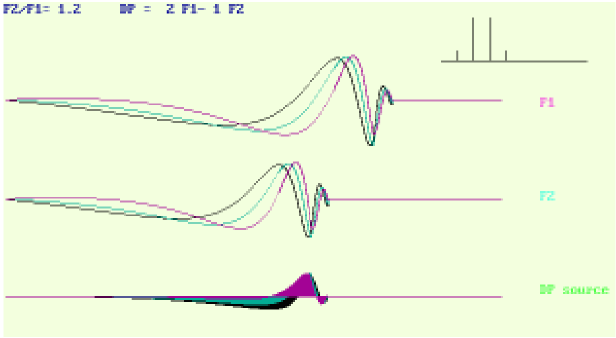
Outer hair cell action is necessarily non-linear. Distortion in basilar membrane motion is therefore inevitable. The force generated by an outer hair cell in response to a sine wave will not be a sine wave, but will be distorted by harmonics. The force generated by a mixture of stimulus frequencies will contain intermodulation components. With two pure tone stimuli with frequencies f1 and f2, intermodulation distortion creates new tones spaced exactly (f2-f1) apart centred on the stimulus tones. Thus f1 is joined by f1-(f2-f1) and f2 is joined by f2+(f2-f1). These formulae simplify to the well known 2f1-f2, 2f2-f1.



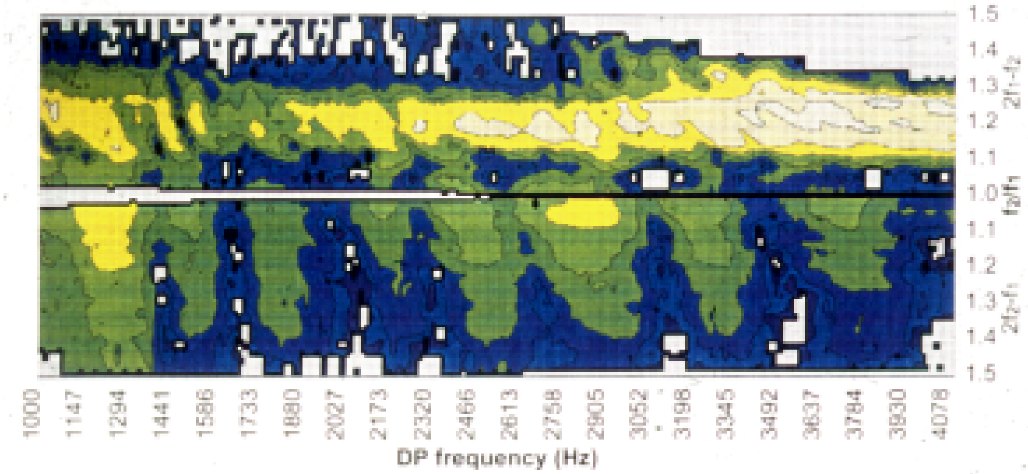
Multiple DPOAEs are produced by two tones (RK)

Intermodulation distortion must be generated everywhere along the basilar membrane that f1 and f2 mix, i.e. everywhere inside the f2 wave envelope.

But the clinical uses of DPOAE depend on the DP emission orginating from a limited spatial region. This is supported by suppression tuning experiments (see **DP experiments**). With certain stimuli, (f2/f1~1.2) the DP 2f1-f2 do appear to come largely from the f2 place. But this is not 100% the case. Other stimulus combinations result in DPs emerging mainly from the DP place. What has emerged from research is that direct transmission of DPOAE from the f2 place requires specific stimulus frequency ratios that result in the array of hair cell distortions are phased along the basilar membrane so that they add up to a reverse travelling wave. DP origin may not be as place specific as we once thought. Current research is focusing on understanding the complex origins of DP emission and this will improve confidence in DPOAE interpretations.



As the stimulus travelling waves progress along the basilar membrane (from black to green to red), the spatial phase pattern of distortion also progresses. Here for f2/f1=1.2 the progression is basal (left). For f2/f1<1.1 the progression is apical (right)



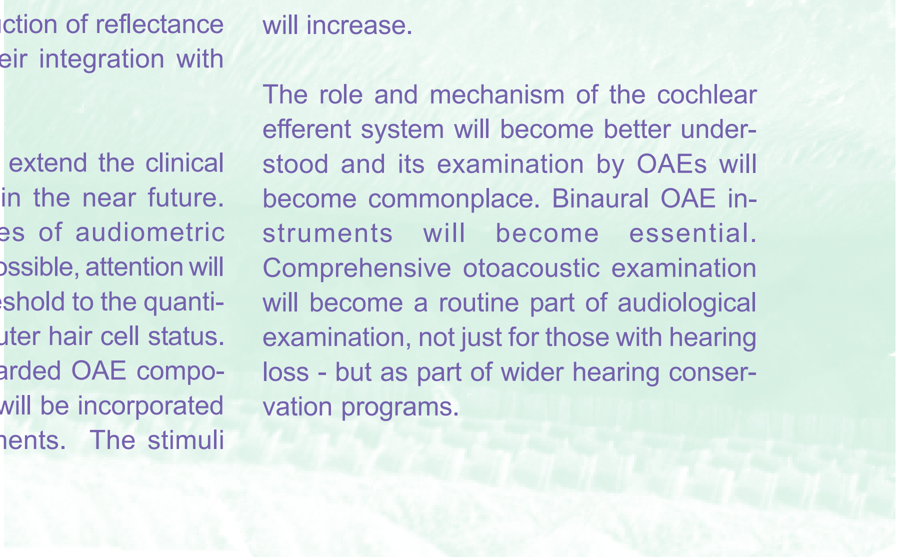
From Knight and Knight 2001, a map of DPOAE 2f1-f2 (upper) and 2f2-f1 (lower) intensity against DP frequency in a single healthy ear for a wide range of stimulus frequency ratio f2/f1. The map demonstrates the complex individual patterns of DP production and reveals the two known transmission paths. The horizonal band (upper) relates to wave fixed (or direct) distortion emission, whereas the vertical bands arise from place fixed (or ‘reflection’) emission.

The future of OAE technology

Technological developments will improve the speed and efficiency of processing and data collection. Meaningful (rather than convenience based) combinations of audiological technologies will evolve. Perhaps the first of these will be the reinvigoration of middle ear examination through the introduction of reflectance measurements and their integration with OAE analysis.

Research will certainly extend the clinical applications of OAEs in the near future. While better estimates of audiometric threshold will become possible, attention will gradually shift from threshold to the quantitative assessment of outer hair cell status. For this, currently discarded OAE components and parameters will be incorporated into routine measurements. The stimuli used for testing will become much more varied with tones and clicks giving way to complex sounds dynamically engineered to probe the characteristics of an individual's cochlear system. As the genetics of hearing loss becomes known, the role of OAEs in the delineation of sub-clinical conditions will increase.

The role and mechanism of the cochlear efferent system will become better understood and its examination by OAEs will become commonplace. Binaural OAE instruments will become essential. Comprehensive otoacoustic examination will become a routine part of audiological examination, not just for those with hearing loss - but as part of wider hearing conservation programs.



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