Understanding and Using

Otoacoustic Emissions

by David T. Kemp

“The incredible turned out to be true!”

Dr. David T. Kemp
Professor of Auditory Biophysics
University College London

Otoacoustic emission is a surprising and exciting auditory phenomenon which allows us to explore peripheral hearing function in unprecedented depth and detail. ‘OAEs’ have given us new insights into deafness and new possibilities for early intervention and treatment.

People often ask what prompted the first OAE measurement. It was to explain a set of complex and little known psychoacoustic phenomena. Spontaneous subjective pure tones had been cited by Gold in 1948 as potential evidence for a ‘cochlear amplifier’. Anomolous aural combination tone generation had been reported by Ward in 1952 involving mysterious internal tones. Finally in 1958 Elliot reported a periodic ripple pattern in the fine structure of the auditory threshold in normal ears. All three were systematically linked together but no rational explanation could be found . Only one physical model seemed to fit the facts. It was that near to threshold levels the healthy cochlea behaved like a reverberating and resonating auditorium enhanced by a strange PA system prone to feedback howl and distortion! It was an incredibly long shot but in June of 1977 I put a microphone into my ear canal just to check. Through the microphone came distortion products, spontaneous tones and echoes! The incredible turned out to be true!

Today clinical OAE measurements are fast becoming a standard part of the audiometric test battery. OAEs have already had a major influence on newborn hearing screening programmes across the USA. But twenty years after the first otoacoustic emission recordings were made at the Royal National ENT Hospital London, many hearing care professionals still feel OAEs to be unfamiliar ‘new technology’. It’s true that OAEs are very different from ABRs. The technical complexity of many scientific papers on OAEs has impeded their assimilation. Commentaries which reproduced misleading and inaccurate ideas about OAEs without scientific foundation have added to the problem.

Fortunately the essential facts about OAEs are not complex. Everyone in audiology should be acquainted with them. The aim of this booklet is to re-present OAEs in a form that is brief, balanced, practical and accurate. Hopefully it will promote the more effective use of this powerful new audiometric tool.

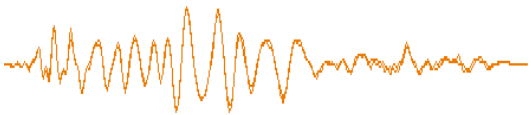
OAE Essentials

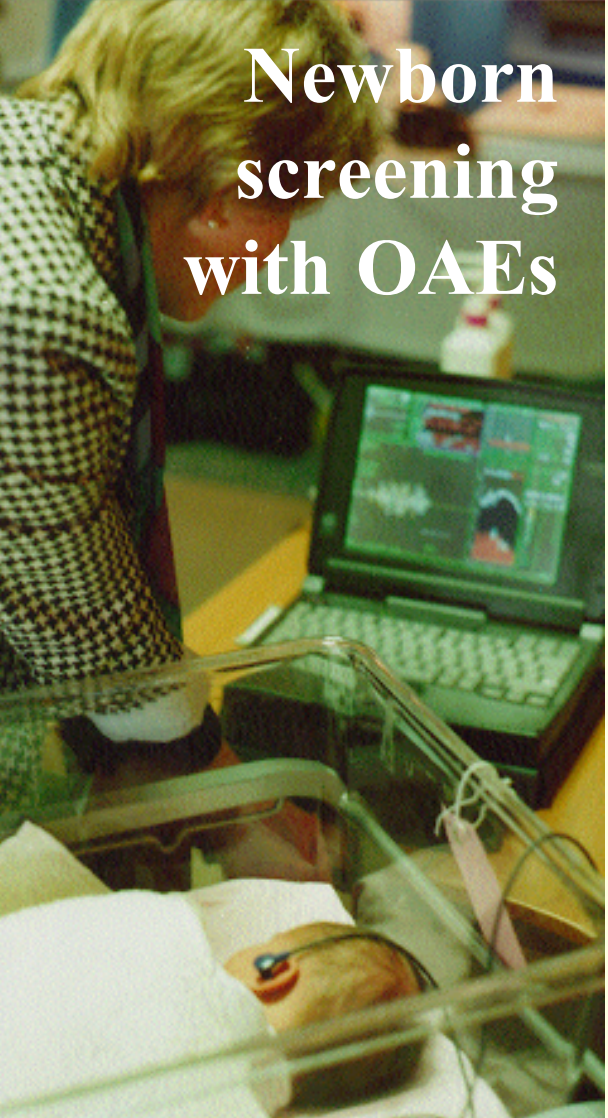
Otoacoustic emissions are small sounds caused by motion of the eardrum in response to vibrations from deep within the cochlea. The healthy cochlea creates internal vibrations whenever it processes sound. Impaired cochleae usually do not. Some healthy ears even produce sound spontaneously as internal sounds are processed and amplified. As described later, the cochlea's capacity to generate sound is intimately associated with its achievement of normal auditory threshold, and the underlying mechanism is very easily damaged.

To record the sounds made by the cochlea an earphone and microphone combination probe is fitted into the ear canal. The middle ear has to be working efficiently in order to conduct the minute cochlear vibrations back to the ear drum - acting like a stethoscope. A good fitting of the probe is important. Closure of the ear canal by the probe greatly increases the sound pressure created by any ear drum vibration. It also excludes unwanted external sounds.

Normally the ear to be tested is given mild acoustic stimulation to evoke an otoacoustic emission. Clicks, tones, noise and even speech all elicit an OAE response. There is a unique OAE response to every stimulus. Depending on the nature of the sound presented, different signal processing techniques are effective in extracting the OAE from the stimulus and other noises. The common technologies are 'TEOAE' when clicks or tone bursts are used, 'DPOAE' when dual tone stimuli are used, and 'SFOAE' when single tone stimulation is used. It is important to remember 'TEOAE', 'DPOAE' and 'SFOAE' instruments deliver different views of the same auditory process and a combination of measurements is needed to get a complete picture.

The essential fact about OAEs is that their presence is always good news about cochlea and middle ear function. It usually means hearing is within normal limits around the stimulus frequency evoking the response - but this is not guaranteed. There can be problems further along the auditory pathway and there is much still to learn about OAEs and cochlear physiology. In the following pages we look at the use of OAEs today for newborn screening and for clinical investigation, and at the auditory physiology and biophysics behind OAEs and OAE technology.





Newborn screening with OAEs

What could be simpler than testing an infant's hearing with an insert-earphone! It takes only a few seconds to record the transient otoacoustic emissions in a quiet office from a typical newborn who has clean ear canals and a well drained middle ear. If conditions are not ideal it can take longer - but 5 minutes is an exceptionally long time for an experienced OAE screener to test a newborn - and it would usually mean that the newborn was not ready to be tested.

Transient OAE technology is generally preferred for screening at this time because the instrumentation provides very fast feedback to the screener on general probe fit, noise and test outcome. DPOAEs can also be used effectively. TEOAE screening has the advantage of testing a wide range of frequencies individually yet simultaneously giving a continuous panorama of cochlear function with frequency. Around 100 universal screening programmes in the USA currently use TEOAEs. A 1996 survey by the National Center for Hearing Assessment and Management (NCHAM) showed referral rate of less than 5%. The reportedly very high sensitivity of the technique for universal screening has not been challenged, despite many hundreds of thousands of TEOAE screenings starting with the Rhode Island Hearing Assessment Project in 1989.

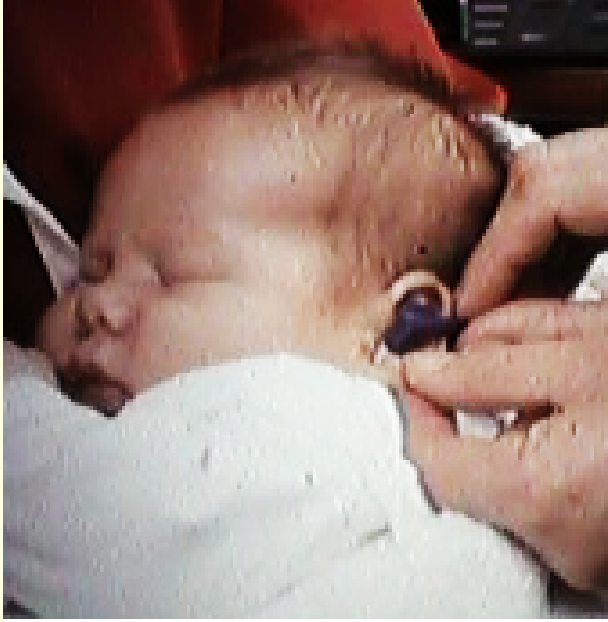
There is an acknowledged learning curve for newborn screening with OAEs. Initial attempts at newborn screening with OAEs can be disappointing unless a few important guidelines are followed. Firstly, probe fitting is paramount. Inspect the ear and select a suitable size of tip. Straighten the ear canal by gently pulling the pinna. Insert the probe firmly and deeply. This opens up the ear canal and excludes external noise contamination. The room need not be audiometrically quiet but continuous background noise should be avoided. Observe the noise received by a suspended probe relative to the instrument's noise artifact rejection range. If the background noise level exceeds 50dBA don't attempt newborn screening.

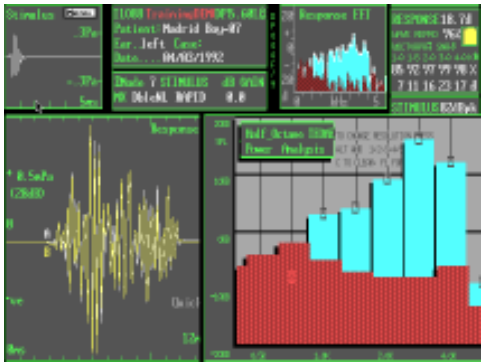
Expect to see some indication of an OAE response in about ten seconds with a newborn. If not - and if both the baby and room are quiet - then assume that the probe insertion has not fully opened up the ear canal or that the disposable tip has become clogged with debris. If having dealt with this there is still no OAE, assume that there is retained fluid still to be cleared from the middle ear,

and retest the baby later. Babies tested on the first day of life more often fail to show an OAE as a result of mild ear contamination - but they usually pass on retest hours later. When OAEs do appear, continue collecting data until the required level of confirmation is achieved. The screener must be trained to judge the technical adequacy of a measurement and to recognise the need for a repeat test. Technical adequacy includes the achievement of the specific statistical and signal-to-noise targets needed to validate OAE responses. Instrument signal processing and automation greatly assist in this process.

It is the responsibility of the audiologist or physician to set an appropriate pass/refer criteria for the baby. The previous gold standard for hearing screening - the ABR - accepted a proven wave V response of normal latency to the selected level of click stimulation as sufficient proof of normal auditory function. By the same standard, any technically valid OAE response within the speech range in response to a click stimulus could be reasonably accepted as proof of adequate cochlea function. In practice, most screening programmes set a more stringent criteria than this. It is common to require OAE responses to be 3 or 6dB above the noise in 2, 3 or more half octave bands between 1 and 4kHz. This exceeds the stringency of the ABR test, and results in a higher refer rate. However the widespread acceptance of multifrequency pass criteria for OAEs must be taken to indicate an underlying dissatisfaction with the non-frequency specific nature of screening ABR. It remains to be seen if such stringent multifrequency OAE pass criteria persist and yield tangible benefits.

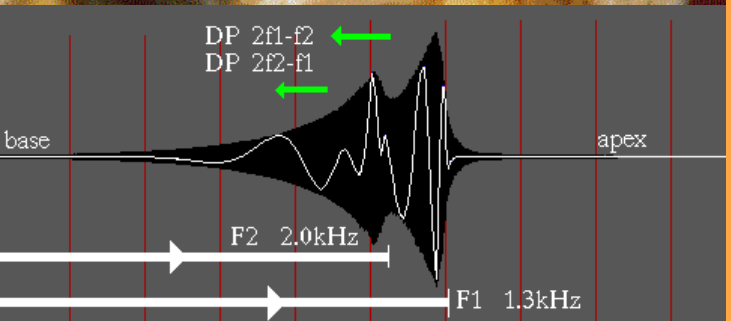
OAE screening has proven very effective in the detection of hearing impairment in newborns, even though the neural pathway is not being assessed. Failure to show an OAE is probably the single most important risk factor for hearing impairment but other risk factors should never be ignored. Any risk of neurological significance means an ABR test *must also* be conducted. To date, among the hundreds of thousands of OAE screenings monitored by NCHAM the incidence of late onset hearing losses missed by OAE screening appears to be very low - around 1% of the hearing impaired population. OAEs appear to be ideal for the first stage of universal screening programmes.





The newborn TEOAE waveform (left) is analysed in half octave bands for assessment (right)

OAEs and the cochlea



The impressive spiral construction of the cochlea (top left) serves only to make the hearing organ more compact. The really important physical feature of the cochlea is the gradually tapering basilar membrane which runs the length of the spiral and carries the organ of Corti with its sensory haircells (lower right). This elastic membrane receives the sound energy delivered to the cochlear fluid by the middle ear. All sounds entering the cochlea result in a ripple wave along the basilar membrane which travels from base to apex. These waves travel hundreds of times slower than sound in air, taking several milliseconds to complete a journey of a few millimetres over the sensory haircells. Each individual frequency component wave grows in intensity as it travels, eventually reaching a peak before coming to a complete stop at a unique place on the basilar membrane (see figure caption below).

The peaking of cochlear travelling waves is crucial to the hearing process. It serves to separate excitation at different frequencies - rather as a prism separates the colors of light (right). Paralleling the eye, the cochlea acts to mould the raw material of sensation, in this case sound, into an image which can be read as a spatial pattern by the array of sensory cells and translated into neural code. The cochlear 'image' projected along the organ of Corti physically represents the external sound environment mapped according to

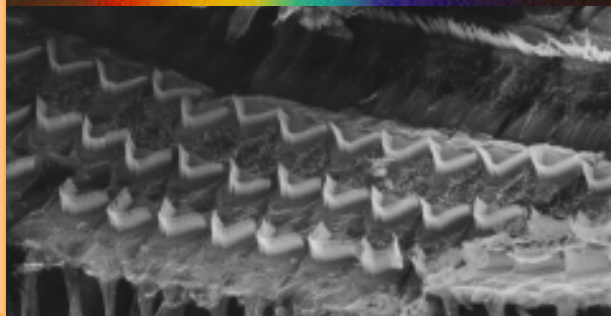
The figure left shows a computer simulated snapshot of waves travelling along the basilar membrane in response to two tones f1 and f2. This is representative of the situation during typical clinical DPOAE measurements. Note how f1 and f2 excite a substantial region of the cochlea, even though their frequencies are very precisely defined. F1 reaches further into the cochlea than f2. Distortion products can only be generated in the region where f1 and f2 overlap. The envelope of f2 defines this region which does not include the geometric mean frequency often wrongly cited as determining the place of DP generation. Higher DPs, such as 2f2-f1, need to be generated even more basally in order to escape the cochlear.

the size of sound sources. Large objects radiating low frequencies are focused at the apex, and high frequency sounds typically radiated from small structures come to focus as the base.

The sensitivity and resolution of the ear depends on two things. One is the size and sharpness of cochlear travelling wave peaks - much as visual acuity depends on the sharpness of focus of the eye. The second is the efficiency of transduction to the auditory nerve. Sound image quality in the ear appears to depend on the health of the outer three rows of haircells, while the single inner row is responsible for the transduction and neural encoding (lower right). Without active outer haircell function, sound energy is lost from the travelling wave before it peaks. Peaks broaden and are of reduced size. Outer haircells generate replacement vibration which sustains and even amplifies the travelling wave, resulting in higher and sharper peaks of excitation to the inner haircells.

Most of the sound vibration generated by the outer haircells becomes part of the forward travelling wave, but a fraction escapes. It then travels back out of the cochlea to cause secondary vibrations of the middle ear and the ear drum. The whole process can take 3 to 15 milliseconds. These cochlear driven vibrations are the source of Otoacoustic Emissions.

Important as OAEs are for probing cochlea function it is ludicrous to suggest that auditory threshold can be reliably measured by OAEs. The crucial mechanism of transduction in the inner haircell is not involved in OAE generation. Furthermore, the mechanism for the escape of energy resulting in OAEs plays no part in the hearing process. This factor certainly accounts for much of the wide variation in the intensity of the OAE responses between individuals and across frequency in the same individual. We would not expect - and we do not observe - more than a 30% correlation between OAEs level and audiometric threshold - far too small for clinical use. But we do observe a very high correlation between the existence of OAEs and audiometric thresholds falling within the normal range. The implication is clear. Most cochlear pathologies involve outer haircell disorder, making OAEs an ideal frequency specific screening test for cochlear function.



Right: Electron micrograph of the surface of the organ of Corti, showing the stereocilia of the single row of inner haircells and three rows of outer haircells.

OAEs in the clinic

As a part of the audiological test battery, otoacoustic emissions can help to differentiate between auditory pathologies and provide useful information for the management of hearing impaired patients.

As reviewed earlier, OAEs have revealed that most cochlear threshold elevations involve a loss in mechanical responsiveness of the basilar membrane to sound vibration. We had no way of knowing this before. Cochlear hearing losses up to around 40dB may be solely due to poor outer haircell performance. The corresponding depression of cochlear travelling wave development and the degradation of the sound image would be adequate to account for the loss in hearing sensitivity. Of course a complementary type of cochlear loss must exist in which the travelling wave develops normally but inner haircells fail to translate the excitory image into neural code. Clinical research is needed to clarify this potential dichotomy. Some hydrops patients do exhibit OAEs with elevated audiometric threshold but most threshold elevations result in absent OAEs.

The logic for the incorporation of OAEs into the audiological test battery is easy to work out once the scope of each test is clearly defined. The pure tone audiogram tests the whole auditory system but includes unwanted central and psychological factors. The ABR tests the auditory periphery and neural pathways as far as the brain stem. OAEs test only the peripheral system - including the organ of Corti - up to the point of excitation of the inner hair cells but not the cells themselves. Tympanometry tests the system up to the cochlea.

When interpreting OAE data it should always be remembered that the cochlea is a frequency specific organ. OAEs - whether obtained by DPOAE or TEOAE - should be considered on a frequency by frequency basis. For example, a patient with normal hearing up to say 2kHz then a precipitous loss will still show OAEs - but only to stimuli containing components in the normal threshold range. Clicks contain all frequencies so will excite an OAE in such a patient - but the OAE response will not include frequency components from within the hearing loss range. This is the meaning of frequency specificity.

In general if there is a hearing problem and there are no other indications, it makes sense for an OAE examination to be the first objective test performed. It is fast and helps confirm normal middle ear *and* cochlear function. In all except newborns an absent OAE should be followed by tympanometry. Absent OAEs with a normal tympanogram usually indicate a cochlear dysfunction but this can sometimes be quite minor. The click stimulus intensity normally used for TEOAEs is around 55dB normal sensation level, but this still provides high sensitivity to losses as small as 15-20dB and even to subclinical factors 4kHz in adults. DPOAEs elicited with stimuli greater than 60dBspl are less sensitive to cochlear dysfunction. 25-30dB loss is needed to abolish the DPOAEs but this sensitivity is maintained up to higher frequencies. A two stage clinical OAE test is recommended - TEOAEs followed by DPOAEs. OAE testing cannot determine auditory threshold. ABR testing is needed to estimate threshold if audiometry is not possible. If OAEs are strongly present with substantial threshold elevation this can indicate a retrocochlear loss, an inner haircell loss, or an inorganic loss.

Auditory nerve pathology often coexists with absent OAEs so that the demonstration of a cochlear component of a hearing

loss by OAEs cannot be used to exclude retrocochlear pathology. However, the presence of OAE with retrocochlear pathology indicates an intact cochlea which may indicate a policy of cochlear preservation during surgery.

In a minority of congenital hearing losses cochlear function remains intact. The provision of amplification to an intact cochlea has to be seriously reconsidered. OAE examination should always precede hearing aid fitment of infants, especially if not used in the identification process. It has been found valuable to re-examine very young and handicapped hearing aid users with OAEs to identify those who actually have normal cochlear mechanical function.

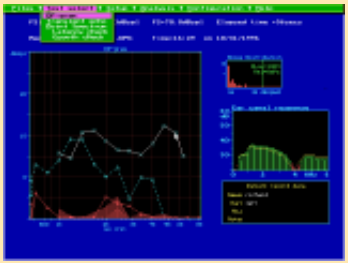
Tympanometry primarily examines the stiffness of the eardrum using low frequency tones. OAEs on the other hand require normal middle ear function from 1kHz to 6kHz. OAEs therefore provide evidence of normal middle ear function, strongly biased towards the transmission properties of the middle ear at speech frequencies rather than its sound reflection properties. This additional information is of course available only where the cochlea is known to be normal. The quality and integrity of surgical reconstruction of the middle ear could be assessed using OAEs.

Although there are wide individual differences in OAE responses, these tend to be stable through time. Small changes in TEOAE patterns not attributable to probe fitting changes, indicate a change in middle ear or cochlear status. This may be used in monitoring chronic conditions or in detecting the effect of occupational noise exposure or the ototoxic effects of drugs. TEOAE monitoring is less effective than DPOAE above 4kHz, but even DPOAEs can be unreliable above this range due to complex ear canal acoustics.

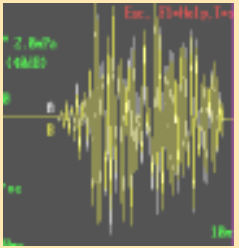
OAE technology - things you need to know

The two major classes of OAE technology -TEOAE and DPOAE - differ fundamentally in the condition of the cochlear which they observe. In TEOAE testing the OAE sound is recorded during the silence between brief stimuli - so that the relaxed status of the outer haircells is observed. As most of the cochlea is excited by a click, reports are simultaneously received from multiple sections of the organ of Corti. This doesn't blur the picture because each section responds at its own characteristic frequency. Signal processing can easily separate the response from each part. A 20ms sweep allows a frequency resolution of 50Hz, or 20 points per octave from 1 to 2kHz. TEOAEs therefore test many parts of the cochlea individually and simultaneously in a functional state close to threshold stimulation. With DPOAEs a more restricted part of the cochlea is more intensely stimulus and continuously driven so that the outer haircells are observed in their 'working state'. The width of the region tested is not defined by the precision of the pure tone frequency but by the natural bandwidth of the cochlea. The stimulated region is quite extensive (see 'OAEs in the cochlea'). Only one or two regions of the cochlea can be simultaneously observed by DPOAEs. This is primarily because modern day transducers produce more distortion than the cochlea if fed with multiple tones. DPOAE measurements must therefore be repeated at several frequencies to get a balanced overall picture. To match the cochlea's natural bandwidth for processing, a 3 points per octave DPOAE resolution is required as a minimum. Higher resolution is desirable so as to overcome the misleading effects of standing wave interference within the cochlea which occur with pure tones.

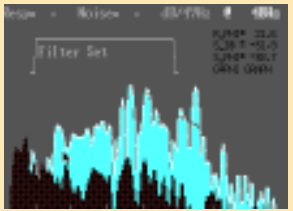
Several distortion products are generated simultaneously



A DP-Gram and TE-Gram compared



A typical newborn TEOAE waveform



A high resolution TEOAE Spectrum

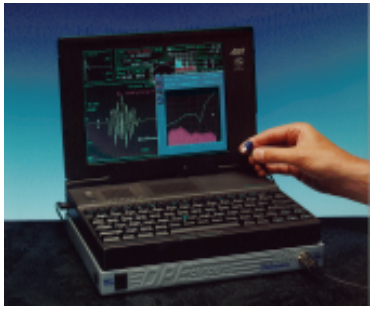
Both DP and TEOAE views of cochlea function are valuable and complementary. Each technology has different advantages and disadvantages. TEOAE technology has the advantages of sensitivity, frequency resolution and speed, but it fails to recover OAEs in adults much above 4kHz. This is due to the shorter latency of high frequency OAEs. DPOAE technology has the advantage of superior detection of high frequency OAEs but it suffers from lower frequency resolution and lower noise immunity at low frequencies. The technique is unable to capture primary OAE energy but a more serious practical drawback is the dependance of DPOAE on the precise stimulus configuration (frequency and level ratios).

Frequency specificity is very important to cochlea function but is often misrepresented in OAE literature. It is the frequency specificity of the cochlea that is important and not that of the stimuli. Clicks or tones are therefore equally suitable stimuli with which to observe the cochlea. All OAEs are highly frequency specific in that each frequency component of an OAE can be directly traced to a frequency component in the stimulus. What is desirable and is often assumed to be true of OAEs is that the response obtained to a specific stimulus frequency tells about the status of a particular PLACE in the cochlea. This is probably true only in a very broad sense.

The relation between OAEs level and auditory threshold - or rather the lack of it - has already been discussed. In the early days of DPOAE research it was common to define a 'DPOAE threshold' as the stimulus level at which the OAE equalled the noise present in the instrument. OAEs do not have a threshold and this measure is unsafe. Threshold is a property of the inner haircells and nerve synapase which play no part in the creation of OAEs. A related and more meaningful measure is the growth rate of DPOAE with stimulus level which appears to steepen as auditory threshold is elevated. Observations must however be averaged over a range of stimulus frequencies and ratios.

The concept of 'passive' and 'active' DPOAE responses arose from animal observations and should be applied with caution to clinical work. Human ears stand much higher levels of stimulation than rodents and 'passive' cochlear responses are very unlikely in response to stimuli of 70dBspl and below. What is more likely is passive DP generation in the probe and instrumentation. DPOAE systems should be checked in a test cavity, but a more powerful test is to measure the latency of DPOAE found in the ear. Latencies of 3ms or greater are highly indicative of a cochlear origin, and lower latencies of instrumentation distortion.

Finally, calibration. In the clinic OAEs systems are used as function detectors, not as measuring systems - but calibration is still important to ensure proper operation and data comparability. OAE systems display sound levels on screen, so the microphone calibration can be quickly checked against a calibrated sound level meter. Stimulus calibration presents special problems due to standing waves in the ear canal. The sound level at the drum cannot be accurately set from measurements at the probe. The problem becomes serious above 5kHz in adults. It is less important in infants. Additionally, the decibel level of the OAE also depends strongly on ear canal acoustics. Considerable technical progress is needed before the ultimate OAEs system is designed.



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