

**Report of an International Expert Symposium on the
usefulness of Otoacoustic Emissions (OAE) Testing in
Occupational Health Surveillance
8-9th February 2011
Manchester, UK**

**Clare Forshaw
Corporate Medical Unit, Health & Safety Executive. Bootle**

This report and the work it describes reflect the outcomes of an expert symposium. The contents, including any opinions and/or conclusions expressed, are those of the delegates and do not necessarily reflect HSE policy

Contents

| | | |
|-------|---|----|
| 1 | Introduction | 1 |
| 1.1 | History of Health Surveillance for Noise induced hearing Loss in Great Britain | 2 |
| 1.2 | Limitations of Pure Tone Audiometry as a tool for occupational health surveillance..... | 2 |
| 1.3 | HSE's interest in Otoacoustic Emissions (OAE) Testing | 3 |
| 2 | Expert Symposium on OAE in Occupational Health | 4 |
| 2.1 | Symposium process | 4 |
| 2.2 | Summary of Discussions | 5 |
| 2.2.1 | What is the relationship between OAE and Noise Induced Hearing Loss? | 5 |
| 2.2.2 | Relevance of OAE for use in occupational health..... | 6 |
| 2.2.3 | What qualifies as an 'acceptable' OAE measure?..... | 7 |
| 2.2.4 | What change in emission is needed to indicate abnormality?..... | 7 |
| 2.2.5 | Distortion Product OAE vs Transient Evoked OAE Methodology..... | 7 |
| 2.2.6 | What are the most appropriate test parameters?..... | 7 |
| 2.2.7 | Practical value of OAE (Added benefit to PTA programme alone)..... | 8 |
| 2.2.8 | Limitations for application in occupational health surveillance..... | 8 |
| 2.2.9 | Gaps/Barriers and Taking the work forward | 8 |
| 3 | Conclusion | 9 |
| 4 | AGREED WAYS FORWARD | 10 |
| 5 | REFERENCES | 10 |

| | | |
|---------|--|----|
| Annex 1 | Summary of Key Literature on Otoacoustic Emissions (OAE) and Noise-Induced Hearing Loss..... | 11 |
| Annex 2 | Letter report on the findings of a review of the literature on otoacoustic emission testing..... | 12 |

1 INTRODUCTION

As the enforcing authority for the Control of Noise at Work Regulations in GB, HSE has responsibility for producing guidance and providing advice to assist employers in meeting their legal duties under this legislation. This includes providing guidance and advice for employers where they need to meet a duty under Regulation 9;

'If the risk assessment indicates that there is a risk to the health of his employees who are, or are liable to be, exposed to noise, the employer shall ensure that such employees are placed under suitable health surveillance, which shall include testing of their hearing.'

Health surveillance is a programme of systematic health checks to identify early signs and symptoms of work-related health in order for actions to be taken to prevent ill health progression and protect workers. The results of health surveillance will be fed back to inform the risk assessment, risk management and review of control processes.

Current guidance on noise health surveillance details regular hearing checks via audiometric testing as the recommended method. This method involves presenting sounds of fixed frequencies and varying intensities to the ear. Pure Tone Audiometry (PTA) is a subjective, behavioural measurement of hearing threshold, as it relies on patient response to pure tone stimuli. PTA involves presentation of pure tones to each ear at specific frequencies, so that the configuration of a hearing loss can be identified.

1.1 HISTORY OF HEALTH SURVEILLANCE FOR NOISE INDUCED HEARING LOSS IN GREAT BRITAIN

Following publication in 1972 of advice on ways of protecting people at work against noise likely to damage hearing, a Working Group was set up to develop guidance in the field of audiometry. The HSE produced a public discussion document in 1978, based on the work of the working group, which was subsequently adopted as a Medical Series guidance note (MS26 "A guide to audiometric testing programmes")

Despite widespread adoption by industry at the time, the scheme for categorisation of audiograms introduced in the discussion document, started to come under some criticism. Concerns were expressed that, amongst other things, there was no provision for early detection of hearing loss. A number of expert seminars were held through the 1990's and research and redrafting took place to revise the guidance and categorisation scheme for the implementation of the new European initiated Control of Noise at Work Regulations in 2005.

Despite redrafting, reemphasis and a new scheme for categorisation with validated reference thresholds, questions are still being raised as to the usefulness of audiometry in allowing preventative action against hearing damage caused by noise at work.

1.2 LIMITATIONS OF PURE TONE AUDIOMETRY AS A TOOL FOR OCCUPATIONAL HEALTH SURVEILLANCE

The limitations of audiometry as a tool for occupational health surveillance include;

- The method only detects hearing damage at a level where damage is significant enough to affect the ability to hear pure tones. This damage is permanent, irreversible and may have been accumulated over many years of exposure not being picked up until it has a realised effect on hearing.
- There is a time lag between hazardous exposure and damage being detected, causing difficulties in the method being able to provide a timely preventative approach to revisiting risk assessment and controls.

- The methodology requires strict test conditions in order to ensure quality of the results. This can compromise repeatability where there are failings, which is an essential element of a health surveillance tool. That is; in order to make judgements on effects of workplace exposures comparisons are made with previous test results
- The test is subjective and requires cooperation from the individual being tested to respond to the pure tone signals being presented. Therefore uncooperative or unreliable individuals will not produce useful results.

1.3 HSE'S INTEREST IN OTOACOUSTIC EMISSIONS (OAE) TESTING

Awareness and control of noise at work has moved on immensely since the early 1980's, yet we are still using the same methodology for health surveillance which has been identified as having limitations for use in this field. HSE is therefore interested in exploring options to improve the standards of noise health surveillance to assist dutyholders in meeting the aspirations of a robust occupational health surveillance model. This should enable early detection of signs or symptoms of ill health, providing useful and timely data that can enable preventative actions in avoiding noise induced hearing damage.

A promising advance in audiological testing has been the advent of otoacoustic emissions testing. OAEs are responses generated by outer hair cells of the inner ear when stimulated by sound transmitted via a small microphone placed in the ear canal via an ear plug. This method has widespread application as a simple, non-invasive, test for hearing defects in newborn babies and young children unable to cooperate in conventional hearing tests. Many western countries now have national programmes for the universal hearing screening of newborn babies.

HSE developed an interest in the potential of this method as a tool for occupational health surveillance in the late 1990's. HSE's activity and involvement in the use of OAE within occupational health surveillance started formally with the funding of a study by Hall & Lutman (2000) who looked at three classes of OAE to assess their repeatability and sensitivity to differences in hearing threshold. The study found that under optimum settings all three classes of OAE proved more reliable than audiometry. The report concluded that OAE methods are twice as sensitive as audiometry to detect change in hearing threshold level and that the methodology offered promise of improved monitoring for noise induced hearing loss (NIHL) in the workplace.

HSE required use of OAE testing as a condition of a now lapsed exemption from the Noise at Work Regulations (1989). This was required as part of an improved occupational health surveillance programme to protect the health of workers covered by the exemption. In notes to support the exemption the test was described as;

- appropriate as a condition due to it being a sufficiently sensitive method to enable early signs of a change in hearing function to be detected.
- would provide objectivity, complementing the audiogram in diagnosis and monitoring.
- would detect noise induced outer hair cell alterations at an early stage
- the results would not be indicative of disability but may indicate susceptibility to any future exposure to loud noises.
- It would be included to help to detect the first signs that there has been damage over the short term.

In 2009 a project was undertaken to develop the capability of staff at HSE's laboratory; HSL (Health and Safety Laboratories) in undertaking and understanding OAE testing. This work involved HSL purchasing the appropriate equipment and meeting with key players to gain a deep understanding of the methodology, its application, benefits and

potential pitfalls. HSL undertook an informal review of the key literature to date (Poole, 2011 unpublished). HSL have recently completed a research project to investigate the optimum test conditions and variability of OAE testing in normal hearing individuals. Key findings were that OAE has good reliability and repeatability in individuals with normal hearing. The smallest difference that can be detected using the technique appears to be small enough to be able to pick up changes that may be expected with noise-induced hearing loss over time and the room in which the measurements are performed (quiet room versus audio booth) had little influence on the reliability of the technique. Thus, a soundproof room may not be necessary to obtain good quality information.

2 EXPERT SYMPOSIUM ON OAE IN OCCUPATIONAL HEALTH

Following years of interest in the potential of otoacoustic emissions (OAE) testing in occupational health HSE decided it was timely to take positive action to make a concerted effort to achieve consensus on the way forward for research and practical application of this test method. An international expert symposium on the usefulness of otoacoustic emissions testing in occupational health surveillance was arranged and attracted the attention of worldwide leading researchers and practitioners in this field. A list of participants is given in Table 1.

Table 1: List of participants attending International Expert Symposium on the usefulness of OAE Testing in Occupational Health Surveillance

| | |
|----------------|---|
| Anil Adisesh | Health & Safety Laboratories, UK |
| Stephen Archer | Occupational Health, Metropolitan Police, UK |
| Borka Ceranic | St Georges Hospital, London, UK |
| Alison Codling | Health & Safety Laboratories, UK |
| Clare Forshaw | Health & Safety Executive, UK |
| David Fox | Health & Safety Laboratories, UK |
| Hiske Helleman | Academic Medical Center, Netherlands |
| Agnes Job - | Institut de Recherche Biomédicale des Armées (IRBA)-France |
| David Kemp | The University College London, Ear Institute, UK |
| Mark Lutman | Institute of Sound and Vibration Research, University of Southampton |
| Lynne Marshall | Naval Submarine Medical Research Laboratory, Groton, Connecticut |
| Arturo Moleti | Dipartimento di Fisica - Universita' di Roma Tor Vergata |
| Annie Moulin | Lyon Neuroscience Research Center, University of Lyon, France (CNRS) |
| Brian O'Reilly | Occupational Health, Metropolitan Police, UK |
| Kerry Poole | Health & Safety Laboratories, UK |
| Dil Sen | Health & Safety Executive, UK |
| Rob Shephard | Consultant Audiologist, SPIRE Hospital Norwich, UK |
| Renata Sisto | Italian National Institute of Occupational Safety and Prevention (ISPESL) |

The aims of the event were;

- to discuss the potential of OAE for use in occupational health surveillance,
- explore the current scientific position,
- to discuss the barriers involved in advocating this new method,
- identify the gaps in understanding and
- decide future direction.

2.1 SYMPOSIUM PROCESS

Following a series of background presentations by the delegates, the group were invited to discuss their experience and scientific knowledge based around a series of key issues presented by HSE at the meeting. These key issues were developed from a review of the literature undertaken by HSE and HSL (attached at Annexes 1 and 2) which identified

relevant gaps in the research evidence. These gaps were identified in the context of what HSE expect OAE to deliver within an occupational health surveillance programme.

The facilitated session aimed to reach consensus amongst the delegates on the relevant issues to the usefulness of OAE testing in occupational health surveillance based on scientific evidence and expert agreement.

Participants present were asked to agree points of consensus where they felt there was strong scientific evidence. The key issues tabled for discussion at the symposium are given in Table 2.

Table 2. Key Issues Tabled for Discussion at the Symposium

- | |
|--|
| <ul style="list-style-type: none">• What is the relationship between OAE and NIHL?• Relevance of OAE testing for use in occupational health surveillance• What qualifies as an acceptable OAE measure?• What change in emission is needed to indicate abnormality?• Distortion Product vs Transient Evoked OAE measures• What are the most appropriate test parameters?• What is the practical value/added benefit?• Are there any limitations to this method that would reduce its usefulness in health surveillance?• Gaps/Barriers. Taking the Work Forward |
|--|

2.2 SUMMARY OF DISCUSSIONS

The following report documents the key areas of discussion relevant to the aims of the session and the consensus points agreed. Where consensus was not reached this does not mean there is no evidence or that there is no support for usefulness in this area. It reflects a lack of consensus on strength of evidence amongst the group, a need for further research, or no clear understanding at this time.

2.2.1 What is the relationship between OAE and Noise Induced Hearing Loss?

The facilitated session first considered the general concept of using OAE within an occupational health setting. Through discussion it soon became apparent that there is a need for agreed common terminology in discussions and reporting in this area.

The group concluded that the exact purpose of the role of OAE testing within an occupational health surveillance programme needed to be established before usefulness and applicability could be agreed. For example, there was a lack of clarity as to whether health surveillance aimed to follow grouped data to identify 'at risk' groups or whether the main purpose was to longitudinally follow individuals for the progression of hearing loss or damage.

There was some discussion on what health surveillance for (NIHL) aims to achieve. Table 3 summarises the thoughts of the group on the strength of evidence for OAE use under a number of potential aims of occupational health surveillance.

It was agreed that the evidence base for the usefulness of OAE is different for monitoring the effect of noise exposure in a health surveillance programme on individuals and groups of workers. The participants agreed that there is strong evidence to support the use of OAE testing to longitudinally monitor groups of similarly exposed individuals and to identify 'at risk' groups at an early stage.

‘At risk’ was found to be difficult to define as the process of damage to outer hair cells picked up by OAE testing and the resulting hearing loss eventually picked up by PTA is not fully understood. However, it was felt there could be confidence that we are identifying subclinical changes to outer hair cells as a result of exposure to noise, which we know is likely to have an effect on hearing ability in the future.

Table 3. Summary of the Symposium Delegates views on evidence for the usefulness of OAE in Occupational Health Surveillance

| Aim of occupational health surveillance | Evidence for relevance of OAE supported? | Comments |
|---|--|--|
| Prevention of damage | Possible | |
| Feedback to employer on effectiveness of controls | Yes with grouped data strong support | |
| Individual management of health effects | A possibility but, not strong evidence yet | |
| Identification of clinical damage/diagnosis | Evidence is sufficiently strong, depending on the specific diagnostic task and the population under test | |
| Biomarker of potential health effect | Yes, depending on the population and diagnostic task | |
| Biomarker of exposure | Yes, depending on the population and diagnostic task | |
| Identify effect of exposure for all workers? | No | Only useful when good OAEs can be measured |

The evidence base supports use of OAE testing for individuals with good OAE emissions at test. As long as there are demonstrable emissions at a baseline test then OAE testing has value for monitoring individuals.

A consensus view on how a health surveillance programme would be structured was to set a baseline with OAE and PTA. Following this periodical monitoring with OAE and only PTA where OAE produced ‘abnormal’ results i.e. large changes in emissions. We are not in a position where PTA would not be considered an integral part of a health surveillance programme for NIHL.

2.2.2 Relevance of OAE for use in occupational health

- There is evidence for a direct correlation between OAE and NIHL, but this is not a 1:1 relationship. This is due to the impact of non noise related issues on other parts of the auditory pathway.
- There is evidence for a well-established causal link between OAE and NIHL in groups of individuals via histopathological studies, animal studies, cross-sectional studies and empirical/anecdotal evidence.
- The evidence base supports use of OAE testing for individuals with good OAE emissions at test.
- OAE reflect outer hair cell damage and outer hair cells are the most sensitive auditory function to noise damage.
- OAEs can therefore have an important role as an earlier indicator of damage/effect of noise exposure.

- OAEs also have a role in identifying temporary threshold shift (TTS) which can be very useful in demonstrating the effect of noise exposure. There is evidence that permanent nerve damage can accumulate from TTS.
- There is a need for the development of an agreed standard operating protocol specific to why the test is being performed.

2.2.3 What qualifies as an ‘acceptable’ OAE measure?

In response to this question the participants again referred to the need to understand exactly what we want the test to do. There is an issue of reproducibility of results when emissions are near the noise floor. However, the noise floor is not the sole determinant of a good recording. The key aspect would be to achieve a good Signal to Noise Ratio (SNR). The group considered that it would be difficult to monitor results longitudinally if the testing programme began with an emission near the noise floor as this erodes reproducibility. Conversely, the results would be considered significant if there was a sudden change from a strong emission moving towards the noise floor. As with PTA, quality assurance issues are important when using the equipment but if good signals were correlated with good thresholds then you could be confident of reliable measurements.

2.2.4 What change in emission is needed to indicate abnormality?

The participants acknowledged that there was difficulty in providing an agreed validated reference point for consistent and standardised advice in this area due to the lack of a normative reference population data. More work is needed in this area.

2.2.5 Distortion Product OAE vs Transient Evoked OAE Methodology

Neither test covers all the frequencies of interest for NIHL. Distortion Product OAE (DPOAE) has strengths in that recent research has shown you can usefully separate the more specific frequency components. The strengths of Transient Evoked OAE (TEOAE) testing are that both click or Maximum Length Sequence (MLS) versions of the methods test a large proportion of the cochlea simultaneously. The group concluded that current evidence supports a combination of both DP and TE OAE methods following each other as a fast and effective way of OAE testing.

2.2.6 What are the most appropriate test parameters?

The participants considered this question but agreed that the most appropriate test parameters would depend on what you want the test to do i.e. different test parameters would be required when testing for vulnerability of future hearing loss (‘at risk’) and looking for mild hearing loss.

It was agreed that care would need to be invested in the testing procedure to ensure good quality emissions and a range of frequencies should be tested and an average taken. DPOAE is currently the method with the most evidence to support its application in this field. However, further research may develop stronger evidence for other methods. There is a need for the development of an agreed standard operating protocol specific to why the test is being performed.

The group noted a need for commercially available equipment geared at occupational use to facilitate research and practical application. The present trend in clinical applications of OAE diagnostics is to propose user friendly instruments based on low frequency resolution DPOAE or conventional TEOAE recordings. Such instruments do not fully exploit the diagnostic potential of OAE. Participants discussed high spectral resolution

DPOAEs and Stimulus-Frequency OAEs (SFOAES) as promising techniques for detecting quality, frequency specific OAE responses.

2.2.7 Practical value of OAE (Added benefit to PTA programme alone)

- Objectivity.
- Specific to outer hair cell damage which is the most vulnerable of the auditory pathway to high noise.
- Detects small changes in the cochlea or in the middle-ear functioning.
- Somewhat less stringent test environment than PTA, although this remains an important test in a robust health surveillance regime.
- Quick.
- 3 stage approach
 - Baseline PTA & OAE
 - Interval OAE monitoring
 - PTA as and when problems identified
- Can alert to other auditory health conditions affecting the cochlea or middle ear.
- Key tool for motivational and educational purposes.
- Can reduce employer liability.
- OAE has a key role as part of holistic approach to hearing conservation.
- The disincentive to investment in advance of PTA techniques is due to the subjective nature of the test and the time factor in achieving increased sensitivity in PTA testing.

2.2.8 Limitations for application in occupational health surveillance

- Lack of normative data.
- Training of technicians is needed, particularly on probe fit and blocking.
- If there is a change in OAE is it necessary to eliminate middle ear cause.
- Tympanometry should be undertaken; particularly at a baseline OAE test (this is more important when setting up an OAE programme of test than for PTA).
- Need to ensure no occlusion of the ear canal.
- Age may affect suitability for testing. However, if emissions are strong enough to allow room for decline to be detected then this is not an issue.
- Consensus that those under the age of 40 are likely to provide 'cleaner' data.
- Hearing threshold levels higher than 30-40dB cause the OAE response to fall close to the noise floor, making the SNR too low to achieve accurate diagnostic information. However, as OAEs are frequency specific, subjects affected by severe hearing loss at certain frequencies, may still have sufficient OAE at other frequencies to be able to usefully monitor effects of noise exposure here.
- The different temporal behaviour of temporary shifts in OAE levels and audiometric thresholds following exposure to high impulse noise levels suggest that time after exposure should be considered a key parameter to be controlled in health surveillance.
- OAEs depend on stimulus level and test parameters so these need to be tightly controlled and of agreed consistency to achieve comparable results.

2.2.9 Gaps/Barriers and Taking the work forward

There was an agreed need to coordinate the development of a validated normal distribution of OAEs. The practicality of achieving this raised the issue that a standardised test methodology would need to be developed in the first instance. An agreement on standard terminology is needed and lack of commercial availability of equipment designed specifically for application in occupational health is a current barrier.

In addition to a number of practical barriers there is also the need to influence behavioural change amongst all players involved in occupational health including employers, workers and occupational health professionals to bring about acceptance of the usefulness of the method.

3 CONCLUSION

There was consensus on many aspects of OAE use in occupational health surveillance. The event has stimulated ideas for collaboration amongst the participants and an electronic forum has now been set up for sharing relevant data to provide a more robust evidence base and the potential for pooling of data for future research is being explored.

- The group agreed that there is strong evidence to support the use of OAE testing to longitudinally monitor groups of similarly exposed individuals and to identify ‘at risk’ groups.
- There is evidence of the usefulness of OAE in the early detection of ‘at risk’ groups following noise exposure from ‘normal hearing’ populations.
- The evidence base supports OAE use in individuals who have clear emissions at recruitment into the programme.
- A combination of both DP and TE OAE methods promises to be a fast and effective way of OAE testing at this time.
- The noise floor should be as low as practicable, but should not restrict testing of individuals who show good SNR.

Next steps for the core group working in collaboration were to;

- Agree some common terms and their meaning in respect of discussions and reporting in the use of otoacoustic emissions testing and occupational health.
- Facilitate collation of normative data as a reference point to establish age related ‘norms’.

Other issues which need addressing are

- The need for an internationally agreed standard operating protocol for OAE testing in occupational health situations.
- The need for commercially available equipment geared at occupational use to facilitate research and practical application.

The symposium has provided a platform upon which we need to build the science in areas where there is doubt and promote the usefulness of OAE in the areas where there is belief amongst experts that there is robust evidence of potential benefit in reducing ill health caused by noise at work. The symposium has provided a forum for future collaboration and sharing of ideas amongst leading experts and HSE. It is hoped that this event has been a catalyst to inspire future research to focus on the usefulness of OAE in occupational health and also be useful in persuading the occupational health community in general of the added value OAE can bring to preventative risk management of noise health risks.

4 AGREED WAYS FORWARD

| ACTION | BY | COMPLETED |
|---|-------------------|--|
| Set up electronic community | HSE (CF) | Feb 2011 |
| Write report of proceedings | HSE (CF) | Expected August 2011 |
| Agree standard procedures and reporting | ALL | |
| Pool/share data sets | ALL | |
| Presence at international conference | HSE (CF) | Presentation at ICBEN Conference, London 25/7/11 Poster presentation at British Society of Audiology Nottingham 7-9/9/11 |
| Agree terminology | ALL, HSE to draft | |

5 REFERENCES

HSE (2006). Controlling noise at work. The Control of Noise at Work Regulations 2005 (L108): HSE Books

Lutman, M.E. and Hall, A.J. Southampton University (2000) *Novel methods for early identification of noise-induced hearing loss*, Sudbury, HSE Books, 49pp.

The Noise at Work Regulations 1989
<http://www.legislation.gov.uk/uksi/1989/1790/contents/made>

Poole, K.P. 2011. Letter report on the findings of a review of the literature on otoacoustic emission testing. Letter report CWH/LET/11/01. Unpublished.

Annex 1

Summary of Key Literature on Otoacoustic Emissions (OAE) and Noise-Induced Hearing Loss

Scope

This summary of the literature is limited to key publications in the last 5 years (using the full scientific papers) and a brief overview of the position up to 2005 (based on accounts given by prominent authors of the relevant scientific studies).

Literature search

A PubMed database search was conducted in order to identify papers. Search terms used were:

OAE AND occupational health, OAE AND hearing conservation programme, OAE AND screening, OAE AND noise induced hearing loss, OAE AND noise induced hearing loss AND susceptibility, OAE AND noise induced hearing loss AND prevention, OAE AND noise induced hearing loss AND detection, and OAE AND hearing thresholds.

Recent key studies

Job et al 2009

A 3-year longitudinal study involving 521 French pilots aged 20 - 40 years was carried out. The aim of the study was to determine whether Distortion Product OAE (DPOAE) method can be used to detect susceptibility to noise-induced hearing loss (NIHL). A sound-proof booth was used, a questionnaire on medical history administered, and otoscopy and tympanometry performed prior to the pure tone audiometry (0.25 – 8 kHz range frequencies) and DPOAE measurements. The pilots were exposed to noise during the 3-year period due to the nature of their occupation. Tests were conducted at least 24 hours after the last period of noise exposure. Details of the OAE method are given. The measurement was considered valid if SNR was equal to or greater than 2 dB. Every intensity point in DPOAE was incorporated into an index based on weighted scores derived using the reference population.

350 pilots (67%) were available to be retested at follow-up. Of these, 160 had at least one ear with a normal audiogram (10 dB HL at all frequencies) at the start of the study (some had both ears, total was 219 ears). A control group of 69 subjects (119 ears) with normal audiograms was available.

The noise-exposed group with normal audiograms at the start of the period were studied. The risk of rapid development of hearing loss that is visible on an audiogram following exposure to noise was doubled in a subgroup of subjects (69 ears) with an initial index greater than 15% from DPOAE measurements when compared with the other subgroup (initial index less than or equal to 15%). Hearing threshold shifts were significantly higher in the first subgroup at the end of 3 years. This may indicate that DPOAE is able to detect susceptible individuals who will develop NIHL; OAE is a more sensitive method if applied to subjects with normal audiograms ie to identify early or minor hearing loss.

Lapsley Miller et al, 2006

A group of 338 sailors (mainly male) were investigated in a longitudinal protocol involving 6 months exposure to noise while at sea in an aircraft carrier. The control group comprised 28 volunteers of similar age from sailors and research staff with no noise exposure. OAE and audiometric thresholds were measured before and after exposure. The measurement collection was constrained by the US Navy protocols and time restrictions for conducting OAE tests. A sound-attenuating booth was used but there were some difficulties with background noise.

Ear canals were screened first and a tympanogram obtained. Pure tone audiometry (with 0.5 – 6 kHz frequency range) was conducted. If the audiometric threshold was less than or equal to 25 dB HL up to 3 kHz or less than or equal to 30 dB HL at 4 kHz, the subject was included in the study. Transient Evoked OAE (TEOAE) measurements were collected and averaged until 260 low-noise averages obtained and considered acceptable if amplitude greater than 0 dB SNR above the noise level. DPOAE f2 1.8 – 4.5 range and cut off was if amplitude greater than the noise level defined by 2 standard deviations above the noise floor. The same methodology was used to retest ears.

A substantial amount of data had to be excluded from the analysis; for example where less than 70% of OAE were measurable for a given frequency. Only results at 2, 2.8 and 4 kHz were available. A group of 75 sailors had relatively complete data sets. There were no significant changes in audiometric thresholds pre and post exposure but there were significant decreases in TEOAE and DPOAE amplitudes. There were no correlations between audiometric results and OAE results but a statistically significant correlation between TEOAE and DPOAE results. Fifteen sailors were diagnosed as having permanent threshold shifts but these ears had many low-level or absent OAEs and significant changes in OAE levels were not observed. The authors calculated using Bayesian analysis that low-level and absent pre-deployment OAEs were predictive of post-deployment permanent threshold shift status; the best measure for this was TEOAE at 4 kHz.

Helleman et al, 2010

A longitudinal study of printing workers was conducted in The Netherlands with a group of 320 employees (316 of whom were men). The age range was 23 to 60 years. Most of the subjects were exposed to noise levels that were between 80 and 85 dB (A). Two assessments of hearing were carried out; follow-up was after 17 months. Only 15 subjects dropped out. A test for conductive hearing problems was included where relevant. A questionnaire on medical history was administered. Temporary threshold shift could not be completely ruled out due to the rotating shift working pattern. Pure tone audiometry covered the frequency range 0.5 to 8 kHz. Ear canals were examined before the OAE tests were performed. The OAE equipment was calibrated daily. TEOAE was measured with 80 pe SPL click stimulus until 280 low-noise averages were obtained. Stimulus levels for DPOAE were L1 of 75 dB SPL and L2 of 70 dB SPL. Ratio of f2/f1 was 1.22 with f2 ranging from 0.841 to 8 kHz. A total of 27 frequencies were tested. There were 3 recordings per frequency. Lower stimulus levels were added at the follow-up testing but the results are not reported in this paper. All tests were conducted using a sound-attenuating booth in a large room with carpet in a relatively quiet part of the building.

A total of 233 subjects had complete data sets after the second measurement. Many single OAE data points were discarded (due to the criterion that SNR should be greater than or equal to 0 to maintain quality). OAE emissions can be low due to hearing damage and those with poor hearing are more likely to have their data discarded. There was some deterioration in audiometric thresholds at the higher frequencies of 6 and 8 kHz. Deterioration was also significant for TEOAE in all frequency bands and the maximum effect was at 4 kHz. The most pronounced changes on a group level were between 4 and 8 kHz in DPOAE. It was not possible to follow changes in emissions below 0 dB SNR for OAE measurements. SNR was higher at the lower frequencies of 1-2 kHz but changes in this region did not have good correlation with changes in higher frequencies.

Sisto et al, 2007

A cross-sectional study was carried out on 217 subjects who have been included in a longitudinal study. The subjects were young workers age 18 -35 years with exposure to various levels of noise at work. All were screened for drugs that are ototoxic and any

relevant pathology. Otoscopy and tympanometry were performed before testing took place. Only subjects for whom other causes of hearing damage other than noise exposure were absent were included in the study. An audiometric booth was used. Audiometry was conducted over the frequency range 0.5 to 8 kHz. TEOAE had a typical noise floor of -12dB. DPOAE f2/f1 ratio was 1.22 (typical noise floor -8 to -15dB). Effective primary levels of L1 = 65dB and L2 = 55 dB were chosen. Data were only included if the actual stimulus used was different from the target stimulus by more than 2 dB to reduce the variability due to fluctuations of the stimulus level. After this, a subset of 160 ears was available for the analyses.

The authors looked at two ways of dividing the subjects into groups for comparison purposes. One set of categories was NORM with audiometric hearing threshold less than or equal to 10 dB (77 ears), MHL with less than or equal to 20 dB and greater than 10 dB at least at one frequency (63 ears) and HL with greater than 20 dB at least at one frequency (20 ears, 4kHz). Statistically significant differences in OAE levels were found between the NORM and HL and between the NORM and MHL categories even though the audiometric threshold differences between categories was small.

The other set of classes consisted of the average values of hearing threshold in 1- 3 kHz range: AVN if average threshold less than or equal to 5 dB, AVM if greater than 5 and less than or equal to 10 dB and AVH if greater than 10 dB. OAE levels were averaged to help overcome the high inter-subject variability. Differences between classes were statistically significant for average TEOAE and DPOAE. TEOAE was only sensitive below 2 kHz unlike DPOAE. Correlation between DPOAE levels and audiometric hearing threshold was sufficient for detection of mild hearing loss (as low as 10 dB in 1-3 kHz range). The authors considered that this OAE method is useful for early detection of damage due to noise on the basis of these results.

Korres et al, 2009

A cross-sectional study was conducted involving workers at a pastry-producing factory at 2 locations in Greece with exposure to similar noise levels of 92 – 93 8-hour dB (A). Workers reported that they did not always wear hearing protection. There were 105 exposed subjects and 34 controls. Those with a family history of hearing loss, previous or active ear infections, previous head injury, use of aminoglycoside medications or age over 55 were excluded. Eighty-six subjects were males, 53 females (age 24 – 54) with 20 males, 14 females (age 25 – 53) randomly chosen in the control group. Otoscopy was carried out to rule out any middle ear pathology and tympanometry yielded normal results. A sound-treated room was used for the pure tone audiometry testing which addressed a frequency range of 0.5 to 8 kHz. DPOAE measurements were made at 1- 6 kHz frequency. The ratio of f2 to f1 was 1.2 and primary tones were 60 and 45 dB SPL for f1 and f2. Sixteen samples were averaged. 2f1-f2 level was compared with the mean noise floor level for each DPOAE measure. If it was included within the 95% CI of the noise floor, the DPOAEs were considered. If it exceeded the upper limit of 95% CI of the noise floor, DPOAEs were considered as present.

Audiometric hearing thresholds were better in the control group subjects. In the exposed group, hearing thresholds were most affected at 4 kHz. DPOAE levels were found to be lower in the noise-exposed group. The maximum response in amplitude occurred at 2 kHz. There was a significant correlation between elevation in audiometric thresholds and decreased DPOAE levels.

Jansen et al, 2009

Professional musicians from 5 orchestras participated in a cross-sectional study of noise-induced hearing loss (NIHL). Of 245 subjects (age 23 - 64), 4 were excluded due to severe hearing loss which was likely to be other than NIHL and 12 did not have complete

data sets because time ran out or the equipment did not function properly. In most cases, pure tone audiometry and OAE tests took place more than 8 hours after the last exposure to music. In 26 subjects, the interval before testing was 4 hours or less. A sound-isolated booth was used and OAE equipment calibrated daily. Bone conduction was investigated when air conductance was greater than 20 dB. Audiometry frequencies tested were 0.25 – 8 kHz. TEOAE was analysed over 1-4 kHz with 80 dB SPL click stimulus. In the case of DPOAE, levels 1 and 2 were 75 and 70 dB SPL, f_2/f_1 was 1.22 and there were 27 f_2 frequencies between 0.815 and 8 kHz. The emission level was determined from 3 presentations. In case of high noise floors, measurement was repeated manually at particular frequencies, usually below 2 kHz. Information on medical histories was collected. Childhood ear infections (41), consultations with an ENT specialist (65) and family hearing problems (89) were discovered.

Most subjects were found to have ‘normal’ hearing according to the audiometry results; a few were in NIHL category and some had age-related hearing loss. The researchers then applied a different set of categories to the study population. Normal hearing (N) had hearing thresholds better than or equal to 15 dB, Notch moderate (NM) had maximum thresholds at 3, 4 and 6 kHz between 15 and 20 dB poorer than the average of thresholds at 0.5, 1 and 2 kHz and at least 10 dB poorer at 8 kHz., Notch profound (NP) maximum threshold level at 3, 4 and 6 kHz at least 25 dB poorer than at 0.5, 1 and 2 kHz, Sloping loss (SL) maximum threshold at 3, 4 and 6 kHz at least 5 dB poorer than average at 0.5, 1 and 2 kHz and at 8 kHz at least 5 dB poorer than the maximum at 3, 4 and 6 kHz, Flat loss (FL) audiograms that did not fall into the other categories with no thresholds exceeding 30 dB and Rest ® not falling into any of the other categories. Most (230) ears fell into the N category with 53 in NM, 41 in NP, 64 in SL, 57 in FL and 35 in R. When notches were observed they were mainly at 6 kHz. Relative thresholds were calculated corrected for gender and age effects according to ISO 7029 standards. The musicians had generally good hearing except at 6 kHz where a higher percentage scored below the reference level (up to the 75th percentile). This indicates NIHL. Large inter-individual differences were seen in the TEOAE and DPOAE results. There was no relation to individual audiometry results but there were clear differences on a group level. Individuals in N category had the strongest TEOAE and DPOAE and there were significant differences between OAE of N and the other categories.

Bockstael et al, 2008

Belgian researchers studied the effect of exposure to impulse noise (163 dB Cpe SPL) using OAE methods. The source of the exposure was gunfire practice (24 subjects) and a 5-day military exercise (31 subjects). The age range was 19 - 48. DPOAE and TEOAE were measured before and after (immediately and after 1 hour of non-exposure). Otoscopy was carried out to exclude middle ear pathology and each volunteer was normal-hearing according to their pure-tone audiometric thresholds before exposure as judged by better than 20 dB HL for 0.125 – 6 kHz and TEOAEs present. TEOAEs were considered present if SNR was above 3 dB SPL in 3 of the 5 frequency bands. No significant changes in OAE levels were observed. This may have been due to the effectiveness of the hearing protectors being used. However, the small shifts in DPOAE amplitudes did not completely recover after the 1-hour of non-exposure. The authors were of the opinion that OAE methods are reliable.

Marshall et al, 2009

Another exploration of the effect of impulse noise involved studying US Marine Corps recruits. The 401 male volunteers had just started basic training. A small control group was obtained from recruits on hold (no weapons training) and medical staff. All participants were age 17 – 28 years. Screening criteria such as clear ear canals, normal tympanograms and audiometric pre-test thresholds of less than or equal to 25 dB at 0.5 –

3 kHz and less than or equal to 30 dB at 4 kHz were applied. 32 controls 285 exposed. Weapons fire above 146 dB pSPL during the 3.5 weeks training. Subjects were noise-free for at least 1 day before the testing. Double-walled sound-attenuating chambers were used for the testing with otoscopy being performed beforehand. Audiometry equipment was calibrated daily. The frequency range was 0.5 – 6 kHz. The TEOAE and DPOAE test methods were the same as those used in Lapsley-Miller et al 2006

Only 60 noise-exposed subjects had a complete data set. Incomplete data sets occurred when there were measurement errors, high noise and/or absent OAEs. There was no statistically significant change in audiometric thresholds between pre-test and post-test but there was a significant decrease in TEOAE and DPOAE levels after the exposure to weapons firing indicating that the OAE method is more sensitive. There was no correlation between shifts in audiometric threshold results and shifts in OAE levels. However, OAE was able to predict a threshold shift, TEOAE at 4 kHz being the best measure for this. Low level or absent OAEs pre-test prevented any demonstration of a shift in OAE post-exposure in some individuals.

Keppler et al, 2010

A reliability study looked at variation in test-retest OAE results in 29 young volunteers (14 female, 15 male) with 56 normally-hearing ears with and without probe-refitting. Both TEOAE and DPOAE were addressed. Test-retest reliability was high. Reliability decreased with increased time interval between testing and with probe-refitting.

Hatzopoulos et al, 2009

A study of 60 subjects with sensorineural impairments in hearing was conducted. 7 subjects were excluded due to either losses below 1 kHz or high slope hearing losses. The remaining 53 subjects were of mean age 39 and comprised 25 males and 28 females. The hearing losses were 25-70 dB HL in the 1-6 kHz range. Otoscopy and bone conduction tests were carried out. Pure-tone audiometry was over the range 0.5 – 6 kHz. It was not clear whether a sound-proof booth was used. DPOAE levels were measured by cochlear scan over 1-6 kHz with stimulus 30 -70 dB SPL. Ten missing cases occurred in DPOAE data. For 5 ears it was not possible to obtain DPOAE threshold estimates. There was good agreement between threshold values and DPOAE levels. There was better agreement between audiometry and OAE results at lower frequencies of 1.5 and 2 kHz possibly due to lower hearing losses at these frequencies. The upper limit for OAE detection of hearing loss was about 40 dB HL (varying with the frequency from 34 to 40).

Summary of recent papers

Three longitudinal and three cross-sectional studies of noise-exposed workers are available. All studies examined the relationship between measured audiometric thresholds and OAE levels.

In the longest longitudinal study, the DPOAE method was found to be capable of distinguishing at the initial assessment between a group that later retained ‘normal’ audiometric results and a group that were ‘normal’ at the start but showed deterioration over a 3-year period. It was determined that low level or absent OAE were predictive of a post-exposure shift in audiometric threshold in another longitudinal study.

Decreases in OAE were associated with exposure to noise. Small hearing losses (up to about 30 dB HL) could be detected using OAE but not all frequencies responded to the same degree. The maximum effect of exposure to noise occurred as a decrease in TEOAE amplitude at 4 kHz.

Information from OAE is limited to ears that have emissions and give a sufficiently high response relative to the inherent noise. As a result, a lot of data were not available in some studies. Where significant hearing loss occurs, OAE output is low in amplitude or absent therefore no useful measurements can be obtained.

Literature up to 2005

OAE measurement has been proposed as a more objective and sensitive test for the effects of noise exposure. OAE levels can discriminate between hearing-impaired and normal-hearing populations and between normal-hearing populations with different levels of noise exposure. OAEs decline with age. In a very large group of people, average OAE level decreased at an earlier age than the decrease in hearing thresholds. Longitudinal studies of noise-exposed groups showed a decrease in OAE amplitudes but no change in audiometric hearing thresholds. It is considered that OAE methods can detect early preclinical changes.

Conclusion

OAE is a method that has some potential for the screening of workers for early NIHL. It has been shown to be more sensitive to the effects of noise exposure. Changes in OAE occur sooner than changes in hearing threshold measured using audiometry. OAE has potential for the diagnosis of a pre-disposition to develop noise-induced hearing loss. OAE is useful for the surveillance of young workers or those with strong OAE; it will not be suitable for some individuals. Pure tone audiometry has to be retained as a standard measure of hearing loss because OAE cannot detect large hearing losses. OAE testing needs to be carried out before too much hearing loss has occurred but this is ideal for giving an opportunity to prevent significant NIHL.

References

Bockstael, A., et al, *Effectiveness of hearing protector devices in impulse noise verified with transiently evoked and distortion product otoacoustic emissions*. Int J Audiology, 2008. **47**: p. 119 – 133.

Hatzopoulos, S., et al, *Estimation of pure-tone thresholds in adults using extrapolated distortion product otoacoustic emission input/output-functions and auditory steady state responses*. Int J Audiology, 2009. **48**: p. 625 – 631.

Helleman, H., W., et al, *Otoacoustic emissions in a hearing conservation program: General applicability in longitudinal monitoring and the relation to changes in pure-tone thresholds*. Int J Audiology, 2010. **49**: p. 410 – 419.

Jansen, E., J., M., et al, *Noise induced hearing loss and other hearing complaints among musicians of symphony orchestras*. Int Arch Occup Environ Health, 2009. **82**: p. 153 – 164.

Job, A., et al, *Otoacoustic detection of early hearing loss in ears with normal audiograms: A 3-year follow-up study*. Hearing Research, 2009. **251**: p. 10 – 16.

Keppler, H., et al, *Transient-evoked and distortion product otoacoustic emissions: A short-term test-retest reliability study*. Int J Audiology, 2010. **49**: p. 99 – 109.

Korres, G. S., et al, *Distortion product otoacoustic emissions in an industrial setting*. Noise & Health, 2009. **11** (43): p. 103 – 110.

Lapsley Miller, J.A., et al, *Low-level otoacoustic emissions may predict susceptibility to noise-induced hearing loss*. J Acoust Soc Am, 2006. **120** (1): p. 280 – 296.

Marshall, L., et al, *Detecting incipient inner-ear damage from impulse noise with otoacoustic emissions*. J Acoust Soc Am, 2009. **125** (2): p. 995 – 1013.

Sisto,R., et al, *Otoacoustic emission sensitivity to low levels of noise-induced hearing loss*. J Acoust Soc Am, 2007. **122** (1): p. 387 – 401.

Annex 2

Letter report on the findings of a review of the literature on otoacoustic emission testing

This review was conducted to help inform discussion at an international symposium on otoacoustic emission testing and its usefulness in health surveillance to be held on the 8th/9th of February 2011. Because of time constraints it has not been possible to search all available literature databases, or conduct a full systematic review. Therefore, the following should be viewed within these limitations.

Scope

The Health and Safety Laboratory were asked to investigate the literature in terms of supporting;

Otoacoustic emission (OAE) testing as a valid technique in providing accurate and repeatable results for occupational health surveillance and under which parameters.

If OAE testing were to be used within a health surveillance setting it would be important to know the following about the technique:

1. That changes in the test are related to the health measure that one is wishing to monitor (in this case noise induced hearing loss).
2. That changes which occur over time are related to changes in health status rather than a lack of repeatability of the technique.
3. That the measurement can be used successfully to collect good quality information on the majority of individuals who would be under health surveillance.

Point 1 will be addressed in a separate review conducted by HSE.

This brief review of the literature, the subject of this letter report, seeks to address points 2 and 3 above. Specifically we aimed to answer the following:

1. Repeatability

Is there any information available in the literature regarding the repeatability of the technique over time and the level of change in response that would need to occur for it to determine a significant change within a health surveillance setting?

2. Measurability

Can acceptable measurements be obtained on a large proportion of individuals tested?

Methods

The published scientific literature was searched using the PubMed database (coverage 1947 to present day) for any paper that contained the term otoacoustic emission and: measurability; reliability; repeatability; accuracy; signal to noise ratio; SNR (signal to noise ratio); applicability

The searches were limited to papers published in English and used adult volunteers.

The resulting searches, which identified 155 potential references, were imported into a reference manager (Endnote v9). Of these 25 were identified by the author to be of potential relevance to the current review questions. Hardcopies of these papers were obtained and reviewed in detail by the author of this review.

Results and Discussion

Repeatability

Fourteen papers were identified which addressed repeatability of OAE and the key findings of these publications are shown in Table 1. Nine of these papers reported information on transient evoked OAE (TEOAE) and eight on distortion product OAE (DPOAE). A variety of statistics have been used to report the repeatability of repeated tests including the correlation between tests, the standard deviation (SD) or the standard error of the mean (SEM) of the differences between tests, and the minimal detectable difference (MDD). It is the latter that is the most useful in determining the extent of any changes in OAE over time that would be perceived as being true changes (over and above the variability of the measurement).

The papers that addressed the repeatability of TEOAE investigated this over a time interval of 0 (i.e. within day) to 238 days. Overall, the papers reporting the correlation between repeated tests of TEOAE have reported correlations between 0.45 and 0.97. From those publications reporting information from which the MDD could be calculated this varied between 4 and 13.6 dB SPL.

For the publications reporting information on the repeatability of DPOAE the correlation between repeated tests ranged between 0.70 and 0.99 with a minimal detectable difference ranging between 4.78 and 11.2 dB SPL. Where information has been reported regarding repeatability at different frequencies the majority report that the repeatability appears to be worse at lower frequencies for DPOAE.

There are a number of factors that vary between the different published studies on repeatability. These factors include the measurement parameters used for both TEOAE and DPOAE, the follow-up times for repeat measurements, the equipment used and the selection criteria for inclusion of data. For example, one study has investigated the impact of the signal to noise ratio (SNR) on the repeatability of data (Keppler et al., 2010). The SNR represents the difference between the measured OAE emission and the background noise level, if it is positive then there is a measurable response over the background noise. In Keppler's study they found that if they split the data into two groups, one group with an SNR of <12dB and the other group with an SNR of ≥ 12 dB, that the correlation and SEM on repeated testing was generally better in the latter group (Keppler et al., 2010).

Two studies have also investigated the repeatability of standard pure-tone audiometry in parallel with studying the repeatability of OAE (Lutman and Hall, 2000; Poole et al., 2010). Both of these studies found that the OAE compared favourably with audiometry, as OAE tended to yield slightly better repeatability.

Table 1 Summary of findings from papers identified investigating repeatability

NH relates to normal hearing, HL relates to hearing loss.

TEOAE relates to transient evoked otoacoustic emission, DPOAE denotes distortion product otoacoustic emission.

Equip avail relates to is the equipment used available commercially.

| Reference | Subjects | Repeatability measured over when? | Sound-proof booth used Y/N/NK (not known) | Equip avail? Y/N | TEOAE correlation | TEOAE (SD [#] /SEM [*] /minimal difference [^]) in dB SPL | DPOAE correlation | DPOAE (SD [#] /SEM [*] /minimal difference [^]) in dB SPL | Comments |
|--------------------------|----------|---|---|------------------|---|---|----------------------------|---|--|
| Franklin et al., 1992 | 12 NH | Short-term: 4 consecutive days Long-term: 4 successive weeks | Y | N | Short-term: 0.54-0.92 Long-term: 0.45-0.89 | Short-term: 2.09-5.04* 2.19-6.80* | 0.70-0.99 0.80-0.99 | 0.74-2.39* 0.87-2.30* | Lowest reliability at 1 kHz for DPOAE. Worst reliability at 4 kHz for TEOAE. |
| Hall and Lutman, 1999 | 38 NH/HL | Two tests over 24 hours to 4 weeks. | Y | Y | | 2.0 [#] | | 3.8 [#] | Reliability for OAE better than self-reported audiometry. |
| Chan and McPherson, 2000 | 30 NH | Short-term: 2 tests repeated within day Long-term: 1 month follow-up | Y | Y | Short-term: 0.54-0.92 Long-term: 0.79-0.93 | | | | Worst short-term reliability at 3 kHz. Worst within month reliability at 1 kHz. |
| Beattie et al., 2003 | 50 NH | a) Immediate re-test b) Very short-term reliability (re-test in 10-20 minutes with probe removal and reinsertion) c) Short-term reliability with retest in 5-10 | Y | Y | | | | Immediate: 1.6-4.6* Very short-term: 2.0-5.5* Short-term: 2.2-5.6* | Poorest repeatability seen at 550 Hz Overall, minimal difference around 14 dB at 550 Hz or 7 dB at 1-4 kHz. |

| Reference | Subjects | Repeatability measured over when? | Sound-proof booth used Y/N/NK (not known) | Equip avail? Y/N | TEOAE correlation | TEOAE (SD [#] /SEM [*] /minimal difference [~]) in dB SPL | DPOAE correlation | DPOAE (SD [#] /SEM [*] /minimal difference [~]) in dB SPL | Comments |
|------------------------|---|---|---|------------------|---|---|---|---|--|
| | | days. | | | | | | | |
| Dreisbach et al., 2006 | 25 NH | Four repeated tests separated by at least 1 week but no more than 2 weeks. | Y | Y | | | | | DPOAE: 88% tests had difference of ≤ 5.99 dB at 4 kHz (difference between test 1 to 4), 12% had difference > 10 dB. For low frequencies (≤ 8 kHz) repeated measurements were within ± 10 dB for between 98.4 and 96%. |
| Wagner et al., 2008 | 40 NH | Group 1: Immediate repeatability assessed by performing 3 tests; then repeated on a following day. Group 2: Three tests repeated with around 5 days between each. | N | N | | | Group 1: 0.74-0.997 Group 2: 0.827-0.979 | 0.27-2.97* 0.77-2.63* | Repeatability poorer at higher frequency and lower primary tone level. |
| Hamdan et al., 2008 | 23 NH singers (1) 23 NH controls (2) 9 HL singers (3) | Two tests immediately after each other. | N | Y | 0.68-0.90 (1) 0.68-0.79 (2) 0.73-0.92 (3) | 2.2-3.8 [#] 1.8-3.5 [#] 0.5 - 5.0 [#] | | | Outcome measure used was SNR. Lowest frequency (1 kHz) gave worst repeatability. |

| Reference | Subjects | Repeatability measured over when? | Sound-proof booth used Y/N/NK (not known) | Equip avail? Y/N | TEOAE correlation | TEOAE (SD#/SEM*/minimal difference~) in dB SPL | DPOAE correlation | DPOAE (SD#/SEM*/minimal difference~) in dB SPL | Comments |
|---------------------------|----------|--|---|------------------|-------------------|--|-------------------|--|--|
| Keppler et al., 2010 | 29 NH | Report repeatability over 7 days. | NK | Y | 0.94–0.97 | 0.73 – 1.01* 2.02-2.81~ | 0.92-0.98 | 0.71-1.60* 1.97-4.43~ | Also investigated the impact of SNR on repeatability by splitting tests into two groups <12 dB and ≥ 12 dB. Intraclass coefficients were greater in those tests with SNR over 12 dB and the SEM was generally smaller. |
| Marshall and Heller, 1996 | 13 NH/HL | Number of tests ranged from 10 to 25. Median time span from first to last session was 55 days (range 21-238 days). | Y | Y | | Highest SD was around 2 dB in the abnormal group | | | |
| Vedantam and Musiek, 1991 | 24 NH | Test-retest between several minutes and 1.5 hours | Y | Y | 0.991 | | | | |
| Roede et al., 1993 | 12 NH | 4 testing sessions. First three separated by 1-week intervals. Last session was 4 weeks later. Overall, follow- | Y | N | | | | 6-9 dB~ | Stimulus level affected the variability with higher levels of L1 giving better reproducibility. |

| Reference | Subjects | Repeatability measured over when? | Sound-proof booth used Y/N/NK (not known) | Equip avail? Y/N | TEOAE correlation | TEOAE (SD [#] /SEM [*] /minimal difference [~]) in dB SPL | DPOAE correlation | DPOAE (SD [#] /SEM [*] /minimal difference [~]) in dB SPL | Comments |
|--------------------------|----------|---|---|------------------|-----------------------|--|-------------------|---|---|
| | | up time around 6 weeks. | | | | | | | |
| Beattie and Bleech, 2000 | 55 NH | Test-retest performed immediately after each other | NK | Y | | | | 3.1 dB* >6 dB [~] | |
| Lutman and Hall, 2000 | 43 NH/HL | Short-term repeatability assessed using tests repeated between 24 hours and 8 weeks. Medium-term repeatability assessed with tests 9 months apart. Long-term repeatability – different group of subjects over 12 years (n=29) | Y | Y | Short-term: 0.65-0.73 | Short-term: 0.81-1.63 [#] at 3 kHz 1.04-1.63 [#] at 4 kHz Medium-term: 1.11-1.81 [#] at 3 kHz 1.25-2.09 [#] at 4 kHz Long-term: 2.3-2.9 [#] (broadband analysis) | | | Audiometry repeatability: Short term: 2.4 to 4 [#] dB Medium term: 2.9 to 5.1 dB [#] |
| Poole et al., 2010 | 33 NH | 3 tests separated by at least one week between them | Y | Y | 0.88-0.94 | 3.4-5.6 [~] | 0.72-0.87 | 5.8-9.6 [~] | Audiometry: Intraclass correlation coefficient between 0.80 and 0.89. Smallest detectable difference between 9.0 and 12.1 dB. |

Measurability

Measurability refers to the proportion of tests conducted which achieve the selection criteria and are thus included in the analysis. Table 2 presents a summary of nine published papers that report information on the proportion of acceptable tests and the selection criteria used. One key criterion that can affect the proportion of acceptable tests is the level of the signal to noise ratio (SNR) used for selecting acceptable data. The SNR is the difference between the measured OAE emission and the background noise level. A range of SNR values have been used which include >0, 3, 6 and 12 dB, with 3 dB being the most commonly reported in these papers. It is clear that even when a cut-off for the SNR of >0 dB is used (i.e. OAE response just measurable over background noise) that a proportion of tests do not meet these criteria (Poole et al., 2010). In this situation it was found that between 96 and 68% of TEOAE tests (depending upon frequency) and between 99 and 82% of DPOAE tests were acceptable (tests at 4 kHz gave the poorest acceptability). One paper has attempted to investigate the impact of different SNR levels on the acceptability of the data (Beattie et al., 2003) . It was found that the SNR had little impact upon the repeatability of the measurement but it was reported that different proportions of tests were found be acceptable with SNR cut-offs of 3, 6 or 12 dB. For example, acceptable measurements varied between 42 and 66% at 0.55 kHz.

Other factors also appear to be important for the acceptability of these data, these include the frequency of the measurement, the test parameters (e.g stimulus level) and the hearing level of the participants. Hearing loss related to exposure to excessive noise tends to occur around the frequencies of 3-4 kHz. Therefore, it is this frequency range that is most interesting from the point of occupational noise health surveillance. In the studies that report the proportion of tests that are acceptable at 4 kHz this varies between 0-70% for TEOAE and 85-96% for DPOAE. The TEOAE 0% reported in the one paper is a little at odds with the other values presented in the same paper (43-79%), and thus this may be spurious because of small numbers. Nevertheless, it is clear from the information available in the literature that acceptable OAE measurements are not achievable on all individuals, and in some cases the proportion of unacceptable tests may be quite high.

Table 2 Summary of findings from papers reporting the proportion of test measurable under different test parameters or selection criteria

NH relates to normal hearing.

TEOAE relates to transient evoked otoacoustic emission, DPOAE denotes distortion product otoacoustic emission.

| Authors | Subjects | Equipment used/ measurement parameters/ selection criteria | Sound-proof booth used? Y/N/NK (not known) | Results and conclusions |
|--------------------------|----------|--|--|--|
| Chan and McPherson, 2000 | 30 NH | IL088 Otodynamics <i>TEOAE</i> : 0.6-6 kHz. 80 dB stimulus. 260 sweeps SNR \geq 3 dB used to inclusion. | Y | The proportion of tests that were acceptable varied between 83% and 100%. |
| Beattie et al., 2003 | 50 NH | Grason-Stadler GSI-60 <i>DPOAE</i> : f2/f1 ratio 1.19 for 550 Hz, 1.21 for 1, 2 and 4 kHz. Stimulus level 65 dB SPL. Noise rejection level of 30 dB SPL. Used SNR values of 3, 6 or 12 dB for inclusion. | Y | Acceptable measurements varied between 42% to 66% at 0.55 kHz, 92% to 98% at 1 kHz, 86% to 96% at 2 kHz and 90% to 96% at 4 kHz. |
| Dreisbach et al., 2006 | 25 NH | Grason-Stadler (GSI-33) equipment. <i>DPOAE</i> : Evaluated a range of different parameters with f2 varying between 16 to 2 kHz using either 25 or 24 points per octave. Stimulus level conditions for L1/L2 were 60/45, 60/50, 70/55 and 70/60. SNR of 6dB or greater used for inclusion. | Y | Using 60/50 % acceptable tests at 9 kHz, 11 kHz, 13 kHz and 15 kHz were 92%, 96%, 84% and 76% respectively. |
| Wagner et al., 2008 | 40 NH | Bespoke equipment used. <i>DPOAE</i> : Used range of primary tones (60, 50, 40, 35, 30, 25 and 20 dB SPL). Range of frequencies 1-6 kHz. SNR \geq 6 dB used for inclusion. Originally had 44 subjects but 4 were excluded because did not meet the SNR of 6 dB. | N | Measurability: (not including those already excluded 4 out of 44); measurement 1 94.7% acceptable, measurement 2 94.2% acceptable, measurement 3 93.2% acceptable. |

| Authors | Subjects | Equipment used/ measurement parameters/ selection criteria | Sound-proof booth used? Y/N/NK (not known) | Results and conclusions |
|---------------------------|--|--|--|---|
| | | Did three repeat measurements. | | |
| Paini et al., 2009 | 141 fishermen and 136 matched controls Divided into 4 groups depending upon exposure. | <i>TEOAE</i> : Stimulus intensity of 80 dB SPL. Noise rejection used 47.3 dB. Reproducibility of 50% or greater with an amplitude of response \geq 3dB used for inclusion. | Y | Proportion of tests meeting the inclusion criteria were lower in the fisherman. At 4 kHz this ranged between 4 and 26% in the fishermen (depending upon the ear tested and the group), however this was not dependent upon noise exposure. The equivalent figures for the controls were 0 to 79%. |
| Xu et al., 1998 | 38 males exposed to occupational noise | <i>TEOAE</i> : IL088 used with stimulus level of 80 dB and 260 sweeps. Divided volunteers into 4 groups based upon whether they had normal hearing (group 1) or had hearing loss of increasing levels (groups 2 – 4). Used SNR of $>$ 3dB for inclusion and reproducibility $>$ 50%. | NK | Proportion of tests not measurable increased with frequency and level of hearing loss. For example, in group 1 with normal hearing at 4 kHz only 70% of tests gave a measurable response. In group 4 (most severely affected) there were no measurable tests at 4 kHz and only 28% at 2 kHz. |
| Vedantam and Musiek, 1991 | 100 NH | IL088 Otodynamics used. <i>TEOAE</i> : stimulus intensity of 83 dB SPL, 260 sweeps. Noise rejection level of 45 dB SPL SNR $>$ 3 dB for selection | Y | At around 0.5 kHz the proportion of tests with measurable OAE was less than 40%, at 2 kHz it was around 95% and then fell to around 65% at 4 kHz. |
| Beattie and Bleech, 2000 | 55 NH | Grason-Stadler, GSI-60 <i>DPOAE</i> : Primary tones for L1 and L2 were equal. Used primary tone levels of 35, 45 and 55 dB. Four pairs of frequencies with geometric means of 531, 1000, 2000 and 4000 Hz (ratio 1.21). Sample sizes of 12, 25, 50, 100, 200 | NK | In some cases the measurability was very low (e.g. 32% at 4 kHz, sample size 200 and stimulus level of 35 dB SPL). The measurability did seem to be dependent upon the stimulus level, sample size and frequency. The greatest proportion of acceptable tests was seen with a stimulus level of 55 dB SPL, frequencies over 1 |

| Authors | Subjects | Equipment used/ measurement parameters/ selection criteria | Sound-proof booth used? Y/N/NK (not known) | Results and conclusions |
|--------------------|----------|--|---|--|
| | | and 400 tested. SNR > 3 dB for selection | | kHz and sample sizes over around 100. |
| Poole et al., 2010 | 33 NH | <p>IL0292 Echoport (Otodynamics) used in both a quiet room and audiobooth.</p> <p><i>TEOAE</i>: Stimulus level of 84 dB and 260 sweeps performed.</p> <p><i>DPOAE</i>: F2/F1 1.22. L1 = 65 and L2 = 55 dB SPL. 3 points per octave.</p> <p>Test with an SNR over zero were included in analysis.</p> | Y | <p>Proportion measurable tests for TEOAE ranged between 96 and 68%. Lowest proportion seen at a frequency of 4 kHz.</p> <p>For DPOAE: proportion measurable tests ranged between 99 and 82% with lowest proportion at 4 kHz.</p> |

Report of International Expert Symposium on the usefulness of Otoacoustic Emissions (OAE) Testing in Occupational Health Surveillance, 8-9th February 2011, Manchester, UK

Summary and Conclusions

This brief review of the literature was conducted to inform discussions and help aid in identifying gaps in the knowledge for an expert international symposium to be held in February 2011. Whilst the review has been conducted carefully it is not intended to be a full systematic review, or a complete evidence base, as all publication databases could not be searched.

This review focuses on two key aspects, which are important if OAE testing is to be used with an occupational health surveillance setting; repeatability and measurability of the technique.

Overall, the literature seems to suggest that the repeatability for both TEOAE and DPOAE is good and may in fact be better than standard audiometry. It should be borne in mind that the majority of the studies investigating repeatability have established this over a very short timescale (e.g. immediately to 1 month). However, there is one study that suggests that repeatability can be maintained for up to 55 days. Further work on longer-term repeatability may be useful in the future, which would provide evidence on the stability of the technique over longer periods likely to be used within a health surveillance scenario.

The evidence available at the moment would suggest that the level of change required over time to be sure of a real change in TEOAE and DPOAE could be up to 13.6 and 11.2 dB respectively. To establish the potential usefulness of this technique, the level of repeatability of the technique needs to be compared to the change one would expect to see in OAE emissions if hearing loss were to take place. This is outside the scope of this current review and is the subject of a separate literature search.

It is clear from the literature that it is not always possible to achieve measurable OAE responses in all individuals. Various factors may influence the measurability of the technique including the selection criteria for an acceptable test, the frequency of the measurement, specific test parameters and the degree of hearing loss. From the literature reviewed there does not seem to be a consensus on the test parameters that should be used or the selection criteria that should be adopted. However, these issues are clearly important in terms of standardising any approach that would be used for health surveillance and therefore this is perhaps one issue that could be addressed at the symposium.

References

- Beattie, R. C. , Bleech, J. 2000. Effects of sample size on the reliability of noise floor and DPOAE. *Br J Audiol* 34(5): 305-9.
- Beattie, R. C., Kenworthy, O. T. , Luna, C. A. 2003. Immediate and short-term reliability of distortion-product otoacoustic emissions. *Int J Audiol* 42(6): 348-54.
- Chan, R. H. , McPherson, B. 2000. Test-retest reliability of tone-burst-evoked otoacoustic emissions. *Acta Otolaryngol* 120(7): 825-34.
- Dreisbach, L. E., Long, K. M. , Lees, S. E. 2006. Repeatability of high-frequency distortion-product otoacoustic emissions in normal-hearing adults. *Ear Hear* 27(5): 466-79.

**Report of International Expert Symposium on the usefulness of
Otoacoustic Emissions (OAE) Testing in Occupational Health
Surveillance, 8-9th February 2011, Manchester, UK**

- Franklin, D. J., McCoy, M. J., Martin, G. K. , Lonsbury-Martin, B. L. 1992. Test/retest reliability of distortion-product and transiently evoked otoacoustic emissions. *Ear Hear* 13(6): 417-29.
- Hall, A. J. , Lutman, M. E. 1999. Methods for early identification of noise-induced hearing loss. *Audiology* 38(5): 277-80.
- Hamdan, A. L., Abouchacra, K. S., Zeki Al Hazzouri, A. G. , Zaytoun, G. 2008. Transient-evoked otoacoustic emissions in a group of professional singers who have normal pure-tone hearing thresholds. *Ear Hear* 29(3): 360-77.
- Keppeler, H., Dhooge, I., Maes, L., D'Haenens, W., Bockstael, A., et al. 2010. Transient-evoked and distortion product otoacoustic emissions: A short-term test-retest reliability study. *Int J Audiol* 49(2): 99-109.
- Lutman, M. E. , Hall, A. J. 2000. Novel methods for early identification of noise-induced hearing loss. *CRC 261/2000*.
- Marshall, L. , Heller, L. M. 1996. Reliability of transient-evoked otoacoustic emissions. *Ear Hear* 17(3): 237-54.
- Paini, M. C., Morata, T. C., Corteletti, L. J., Albizu, E., Marques, J. M., et al. 2009. Audiological findings among workers from Brazilian small-scale fisheries. *Ear Hear* 30(1): 8-15.
- Poole, K., Codling, A. , Frost, G. 2010. Optimum test conditions and variability of otoacoustic emission testing in individuals with normal hearing. *Draft report for HSE. CWH/10/02*.
- Roede, J., Harris, F. P., Probst, R. , Xu, L. 1993. Repeatability of distortion product otoacoustic emissions in normally hearing humans. *Audiology* 32(5): 273-81.
- Vedantam, R. , Musiek, F. E. 1991. Click evoked otoacoustic emissions in adult subjects: standard indices and test-retest reliability. *Am J Otol* 12(6): 435-42.
- Wagner, W., Heppelmann, G., Vonthein, R. , Zenner, H. P. 2008. Test-retest repeatability of distortion product otoacoustic emissions. *Ear Hear* 29(3): 378-91.
- Xu, Z. M., Van Cauwenberge, P., Vinck, B. , De Vel, E. 1998. Sensitive detection of noise-induced damage in human subjects using transiently evoked otoacoustic emissions. *Acta Otorhinolaryngol Belg* 52(1): 19-24.