Chapter 4
Otoacoustic Emissions

The discussion thus far has provided the background to the study in the areas of occupational health and occupational audiology, NIHL and financial compensation for the damage caused by exposure to occupational noise. An investigation of Otoacoustic emissions (OAEs), as set out in this chapter, will contextualise the study further.

The clinical application of OAEs has become an integral part of the audiological evaluation, and is a sensitive measure of cochlear outer hair cell (OHC) function (Hall, 2000: 25; Lutman & Hall, 2000; Musiek & Baran, 1996; Namyslowski, Morawski, Urbaniec, Trybalska, & Lisowska, 2001; Yoshida, Aoyagi, & Makishima, 1995). NIHL is known to cause a reduction in cochlear function as a result of OHC damage (Avan & Bonfils, 2005; Balatsouras et al., 2005; Chan et al., 2004; Chen & Zhao, 2007). The use of OAEs in the context of NIHL is therefore valid and has the potential of becoming an essential aspect of diagnosis of NIHL (de Koker, 2003; Clark, 2004; Khoza, 2008).

4.1 Definition of Terms

OAEs are classified according to the stimulus used to elicit the emission and fall into two classes: the spontaneous and the evoked OAEs (Hall, 2000:15). The taxonomy for OAEs is based on the theory that they arise from nonlinear, electromechanical distortion within the human cochlear, which creates a source of energy that is measured in the outer ear as an emission (Gorga, Neely, Ohlrich, Hoover, Redner & Peter, 1997; Gorga, Nelson, Davis, Dorn & Neely, 2000). Spontaneous OAEs require no stimulus and thus far have proved to have little clinical value (Hall, 2000:15).

Evoked OAEs can be divided into:

- Transient Evoked OAEs (TEOAEs), which require a click stimulus;

- Stimulus Frequency OAEs (SFOAEs), which require a continuous pure-tone stimulus; and
- Distortion product OAEs (DPOAEs), which require two pure tones as the stimulus to evoke the emission (Martin, Jassir, Stagner & Lonsbury-Martin, 1998; Shera & Guinan, 1999).

The two types of evoked OAEs that are most commonly used in clinical evaluation, and that are included in most commercially available instruments, are DPOAEs and TEOAEs. If there is a normal middle ear function, the presence of OAEs implies functioning OHC and consequently, hearing thresholds within normal limits (Yeo, Park, Park & Suh, 2002). Conversely, the reduction of amplitudes or absence of OAEs suggests a disruption in function of OHC with the implication of some degree of hearing loss. TEOAEs have been shown to be absent when a hearing loss is greater than 30 dB HL but DPOAEs can still be measured when a hearing loss of 50 – 70 dB HL exists (Gorga et al., 1997).

Since this current study population had a high prevalence of existing high frequency sensorineural hearing loss greater than 30dB HL, only DPOAE measures were used in the clinical setting and are therefore the only type of OAE reviewed in this study.

4.2 Distortion product otoacoustic emissions

4.2.1 Stimulus parameters of DPOAEs

DPOAEs are elicited by the simultaneous presentation of two primary frequency tones, known as f_1 and f_2 (Hall, 2000:22). Studies investigating the ratio that yielded the maximal DPOAE amplitude and therefore, the most clinically useful DPOAE, occurs when the intermodulation of the primaries is $2f_1 - f_2$ and the ratio between the two frequencies (f_1/f_2) is 1.2 (De Waal, 2000; Dhar, Talmadge, Long, & Tubis, 2002; Dhar, Long, Talmadge, & Tubis, 2005; Gorga, Neely, Dierking, Kopun, Jolkowski, Groenenboom et al., 2007; He, Nuttall, & Ren, 2007).

The stimulus used to evoke DPOAEs potentially has an infinite array of intensity and frequency combinations. Clinical and laboratory studies to find the best combinations have resulted in stimulus parameter protocols that are currently used in commercially available measurement instruments (Dhar et al., 2005; Franklin, McCoy, Martin, & Lonsbury-Martin, 1992; Gorga et al., 2007; Gorga, Neely, Dierking, Kopun, Jolkowski, Groenenboom et al., 2008; Hall, 2000:22; He et al., 2007; Johnson, Neely, Garner, & Gorga, 2006; Keefe, Ellison, Fitzpatrick, & Gorga, 2008; Lucertini, Moleti, & Sisto, 2002; Marshall, Lapsley Miller, & Heller, 2001).

Another stimulus factor that influences the DPOAE amplitude is the loudness level ratio of the primaries namely, L1 an L2. The loudness level ratio that yields the maximum DPOAE amplitude is reported to be when L1 is greater than L2 and when L1-L2=10 dB SPL is used (Delb et al., 1999; De Waal, 2000). Contrasting evidence of L1-L2=25 dB and f1/f2=1.18 achieving improved results in detecting noise damage to the cochlea shows that these variables should be chosen purposefully in the clinical environment because they influence the results obtained. The nature of the population being tested should also be taken into account e.g. noise-exposed workers, to enable improved comparison between DPOAE amplitudes and pure-tone thresholds (De Waal, 2000; Delb et al., 1999; Stover, Gorga, Neely, & Montoya, 1996).

Other stimulus protocols that have been investigated are Input/Output protocols which use and the use of the time domain or the latency of a DPOAE measure (Goldman et al, 2006; Boege & Janssen, 2002; Dhar et al., 2005).

4.2.2 Application of DPOAEs

Optimal application of the OAE test and more specifically of the DPOAE test procedure is evolving and holds the potential for advances in clinical uses in the future (Hall 2000:26). Some of the well documented clinical applications of OAEs are newborn screening, peadiatric audiometry and central auditory processing differential diagnosis. Further uses and applications more relevant to this study are the monitoring of site-specific cochlea dysfunction as a result of ototoxicity or of noise exposure (Khoza, 2008; Duggal & Sarkar, 2007; Campbell, 2004; Chen & Zhao, 2007) and for use in the assessment of suspected functional hearing loss or pseudohypacusis (Balatsouras et al., 2003).

4.2.2.1. Limitations of the use of DPOAEs

Despite the value added to clinical practice through the use of DPOAEs the limitations of the test must be taken into account. The main limitation of the use and application of DPOAE testing is that, despite its ability to differentiate between cochlea and retro-cochlea dysfunction when used in a test battery alongside other test procedures, it is not a test of hearing. In contrast, the current gold standard for testing hearing, the behavioural audiogram, has the audiological value of being a test of hearing. An audiogram provides information regarding both the inner and outer hair cell integrity and is dependent on input from the eighth nerve as well as the central auditory system. Conversely, the DPOAE only provides site specific information on the integrity of the outer hair cells and is purely a pre-neural response. As a low energy signal the DPOAE requires the external management of the low energy signal by means of computer hardware, software as well as algorithms to render the responses clinically useful (Hall 2000:25; Engdahl et al., 2005; Green & Huerta, 2003). Another limitation of the use of the valid and reliable use of DPOAEs is due to the effect of a middle ear pathology that will influence the propagation of both the inward and outward signal of the DPOAE. Since there is a relationship between the status of the external auditory canal and middle ear with the intensity of the emission, it becomes critical to verify status of outer- and middle ear system prior to implementing DPOAE measurements.

4.2.2.2 Specificity of DPOAE measurements

DPOAEs have been shown to distinguish reliably between normal and abnormal ears and they are regarded as a valid measure of cochlear function (Gorga, Neely, & Dorn, 1999; He et al., 2007; Lapsley Miller, Marshall, Heller &

Hughes, 2006; Shera & Guinan, 1999). In addition to the sensitivity of DPOAE methods, research has shown a satisfactory level of inter-test repeatability between different audiologists as well as for different instruments (Franklin et al., 1992; De Koker et al., 2003; Clark, 2004; Lapsley Miller et al., 2006).

4.2.2.3 Degree of hearing loss

The high degree of sensitivity of OAEs to cochlea damage is also relevant for a discussion on the relation of OAEs to diagnosing hearing loss (Hall 2000:259). When the emission amplitudes are within normal limits the clinician assumes that hearing thresholds are also within normal limits. This relationship affords the clinician a diagnostic tool when the hearing thresholds are normal but the OAEs are abnormal or visa versa, of investigating further and tracing the either the measurement errors, the lack of co-operation in testing or the site of lesion of the hearing loss. For this reason too, the OAE measurement technique affords the clinician the opportunity to identify early evidence of damage to the outer hair cells either from noise or ototoxicity (Clark, 2004; De Koker et al., 2003; Campbell, 2004). Mild-to-moderate hearing loss of 16 dBHL to 45 dBHL are known to result in abnormal or a lack of detectable emissions (Hall 2000:260). In the majority of ears with sensory hearing loss of 40 dBHL or more , OAEs are not observed (Hall, 2000:261).

4.2.3 Interpretation of DPOAEs

The accepted clinical procedure for measurement and interpretation of DPOAEs is, firstly, to ensure that there are no outer- or middle-ear pathologies that will confound the results (Yeo, et al., 2002); secondly, to ensure that the test environment has low ambient noise levels; and, thirdly, to perform a replicated recording that confirms the results (Hall, 2000:139).

The second criterion, low ambient noise level, is expressed as the difference between the emission level (DP) and the noise floor (NF) and is known as “DP-NF”. The criterion for the acceptance of a signal as an emission is dependant on the population and the application of the OAE results (Hall 2000;135). A widely used clinically acceptable level of ambient noise is attained when the DP-NF is 10 dB SPL or greater because, when the difference is that large, the clinician can be confident that the measurement is a valid indication of cochlea function and that the result has very little interference from ambient noise in the test environment or artefacts from measurement. In contrast however, studies have shown that a DP-NF of 6 dB SPL, and even as low as 3 dB SPL, can be used as acceptable DP-NF differences (Chan et al., 2004; Cilento, Norton, & Gates, 2003; Hall & Lutman, 1999). Moreover, Cilento et al. (2003) reported that, when deciding on an effective criterion in the cross-sectional study on age changes in DPOAEs, the comparison of a DP-NF difference of 0 dB SPL and 6 dB SPL, indicated no differences in the number of analysable emissions.

Knowledge of the expected DP-NF differences in a mining population is lacking, especially with regard to the effect of noise exposure on the relationship between emission level and noise floor levels. The current study therefore provides an opportunity to describe the expected DP-NF characteristics in a noise-exposed population and to evaluate these against the standard criteria for interpretation of DPOAE as discussed later in section 6.5.2.1. The results may provide the clinician with normative data on which to base clinical decisions such as whether to suspect pseudohypacusis in a client's results or whether to make adjustments to the testing environment.

The measurement and recording of DPOAEs are a complex combination of the input sound and the environmental noise combined with the output from the ear. Studies have investigated the way in which the minute emissions which emanate from the ear canal during testing are recorded by the microphone and the different methods that can be used to process and analyse these recordings. Some of the signal-processing tools which have been reported with varying levels of improved clinical use include:

- the use of $2f_1$-f_2 vs $2f_2$-f_1 (Gorga et al., 1999; Gorga et al., 2000, Shaffer, Withnell, Dhar, Lilly, Goodman & Harmon, 2003.);
- the use of the discrete Fourier transformation (Boege & Janssen, 2002);

- the use of inverse Fast Fourier transformation with time window and low pass filter (Shaffer & Dhar, 2006);
- the use of nonlinear adaptive signal processing techniques (Ziarani & Konrad, 2004); and
- the use of latency measurements using phase gradient (Ma & Zhang, 1999).

A clinician may use the default settings on a commercial DPOAE measurement instrument accepting the settings or the signal stimulus and processing methods set by the manufacturer with little awareness of the extensive potential in the frequency specificity of the selected protocol nor the impact of the settings on the measurements (Hall 2000,132-140). However, all these have an impact on the time taken to make sufficient recordings, the tolerable ambient noise levels, and the acceptable percentage of error (Ziarani & Konrad, 2004). Improved clinical knowledge from the current study about alternative settings and population-specific settings will enhance the clinical use of the test. The current study used the manufacturer default settings with stimulus frequencies in 1.2 ratio for f1/f2; the intensities of the stimuli were L1-L2=10dB SPL (L1=65,L2=55); and the signal processing used $2f_1$-f_2.

4.3 Characteristics of DPOAEs

4.3.2 Gender

Gender affects many tests of the auditory system, as highlighted in the discussion on behavioural audiograms in a noise-exposed population (Dunckley & Dreisbach, 2004). DPOAEs have also been found to exhibit gender-related differences, where females tend to have larger emissions than men when elicited with lower-frequency stimuli. (Dunckley & Dreisbach, 2004; Engdahl, Tambs, Borchgrevink, & Hoffman, 2005; Schmuziger, Probst, Smurzynski, 2005). Women reportedly lose DPOAE amplitude from both age and hearing threshold loss but men lose more DPOAE amplitude than women proportional to the degree of loss of hearing (Cilento et al., 2003). The sample for this study contained only males, as described in the methodology section (see Chapter Six); further exploration of the gender differences in DPOAE is therefore not relevant for this study.

4.3.3 Age

Early research results were undecided on whether age-related differences that were not related to hearing levels occurred when measured with DPOAEs (Dorn, Piskorski, Keefe, Neely, & Gorga, 1998). In many cases the early research made use of small sample sizes or the hearing levels of subjects were not strictly selected (Hall, 2000). More recent research with large sample sizes and more stringent selection criteria has indicated that statistically significant interactions occur as a result of age (Dorn et al., 1998).

DPOAE amplitudes decrease, albeit by small magnitudes, as age increases (Dorn et al., 1998; Uchida, Ando, Shimokata, Sugiura, Ueda & Nakashima, 2008). The finding that DPOAE amplitudes deteriorate with age has led to the hypothesis among researchers that there may be a process specific to aging that affects the generation of DPOAEs (Dorn et al., 1998; Uchida et al., 2008). The effect of age on DPOAE levels has been shown to parallel the decline in the high-frequency hearing threshold levels (Cilento et al., 2003). However, the critical age for a decrease in DPOAE levels has been reported to be 30 years of age, while, for hearing threshold levels, the age when most deterioration occurs is above 50 years (Johansson & Arlinger, 2003).

The rate of decline in DPOAE amplitudes is less than for hearing threshold levels (Cilento et al., 2003) and plateaus above the age of 60 to 65 years. The rate of decline is reported to be influenced by gender, with women showing a decrease independent of their hearing thresholds while in men decreases in DPOAE amplitudes are not dependent on the hearing threshold (Cilento et al., 2003). The reported rate of decrease in DPOAE amplitudes ranges from as little as 1-2 dB SPL (Cilento et al., 2003; Gates, Mills & Rubel, 2002) to as much as 8 dB SPL per decade of aging, with the largest differences occurring during the 20-29 years and 30-39 years' period (Johansson & Arlinger, 2003). The interaction between age and noise exposure was controlled in the study on the adult Swedish population (Johansson & Arlinger, 2003), but in most other reported studies noise-exposed subjects were included in the sample (Cilento et al., 2003; Engdahl, 2002) and therefore the contribution of noise damage to the reported decline in amplitude with age has not been clearly distinguished. Information on longitudinal changes in DPOAEs is lacking, with the exception of the study on naval recruits who were exposed to gunfire while on long-term duty. This study found that the increase in hearing threshold levels was 1.2 dB per annum while the DPOAE amplitudes decreased by 0.9 dB per annum (Lapsley Miller et al., 2006). The current study provides an opportunity to evaluate the separate effects of age and noise exposure on the DPOAE amplitudes by comparing the results with those of the Swedish population-based study (Johansson & Arlinger, 2003).

4.3.4 Ethnicity

Differences in the amplitudes of OAEs between ethnic groups have been proposed to be possibly due to melanin level differences in the cochlea, and middle ear mechanical and anatomical conduction differences (Dreisbach, Kramer, Cobos, & Cowart, 2007). Spontaneous Otoacoustic Emissions (SOAEs) were found to occur in larger numbers and at higher frequencies in African Americans and Asians compared with Caucasians (Dreisbach et al., 2007). Similarly, TEOAE amplitudes are reported to be significantly higher in young Chinese subjects than in Caucasians (Shahnaz, 2008). No significant differences were found in the characteristics of DPOAEs when comparing young normal hearing male Caucasians, African Americans and Asians (Dreisbach et al., 2007; Hall, 2000).

In a noise-exposed population, the only reference to possible ethnic differences in OAE characteristics in the research literature is also in the South African mining environment (de Koker et al., 2003). De Koker et al. (2003) found that, when investigating the feasibility of using OAE methods for screening early hearing impairment in South African mineworkers, there appeared to be differences between measurements in Caucasian and African subjects for both the TEOAEs and the DPOAEs. The sampling strategy was given as a possible reason for this finding and it was suggested that further investigation was needed (de Koker et al., 2003). The current study provided a possible comparison of ethnic groups to investigate the suggestion of ethnic group differences in DPOAE levels in the mining population further.

4.3.5 Occupation

As discussed in Chapter two differences in audiometric configurations have been reported in noise-exposed gold miners who work in different occupations. Similar investigations into the DPOAE characteristics of noise-exposed workers is lacking limiting our knowledge. Therefore, this current study will provide an opportunity to investigate the possible similar patterns in DPOAE levels and to compare the results with the NIHL characteristics in different occupations, thereby also improving the knowledge of the relationship between the two test types.

4.4 NIHL and DPOAEs

Considerable basic research on animals has shown sensitivity and specificity of DPOAE measures in identifying noise-damaged cochlea when using electrophysiological measures of cochlear status (Davis, Qui, & Hamernik, 2005; Chung ,Ahn, Kim, Lee, Kang, Lee, et al., 2007). It has since been argued that DPOAEs are a viable means to monitor cochlear function for both pre-symptomatic identification and hearing conservation programme monitoring purposes (Bockstael, Keppler, Dhooge, D'haenens, Maes, Philips et al., 2008; Harding & Bohne, 2004; Probst, Harris, & Hauser, 1993; Vinck, 1999; Vinck, Van Cauwenberge, Leroy, & Corthals, 1999).

Researchers have investigated the effects of intense noise exposure on the OHC in guinea pigs, rats and chinchillas (Chen & Zhao, 2007; Chung et al.,2007, Harding & Bohne, 2004; Sliwinska-Kowalska & Jedlinska, 1998; Yoshida et al., 1995). The conclusions from these animal studies indicate that, both in temporary threshold shift (TTS) and in NIHL development, noise can impair the micromechanics of the OHC and might consequently impair OHC electromotility to induce a threshold shift (Chen & Zhao, 2007; Davis, Qui, & Hamernik, 2005; Eddins, Zuskov, & Salvi, 1999). Prolonged exposure to industrial noise is reported to cause a fast increase in hearing threshold levels in most animals by four weeks of exposure (Sliwinska-Kowalska & Jedlinska, 1998). Microscopic investigation of the OHC indicated that the first 30 dB of permanent hearing loss was caused by damage to the OHCs but that the progression in cochlea pathology did not correlate well with the progression of the degree of hearing loss (Sliwinska-Kowalska & Kotylo, 1997; Sliwinska-Kowalska & Jedlinska, 1998). The early stages of NIHL, where there is less than 20% OHC damage, have been shown to have a normal audiogram while when OHC damage is greater than 25 – 30% the effect can be seen on the audiogram (Hall & Meuller, 1997; Hall, 2000; Skellett, Crist, Fallon, & Bobbin, 1996).

The limiting factor relating to the use of DPOAEs in a noise-exposed population is that in many cases the population has pre-existing hearing loss and therefore OHC damage. The DPOAE amplitude is reduced whenever there is a mild-to-moderate degree of hearing loss and as the hearing thresholds increase, the probability of detecting DPOAEs becomes less likely (Harrison & Norton, 1999; Johansson & Arlinger, 2003; Kim, Frisna & Frisna, 2002; Konopka, Pawlaczyk-Luszczynska, Sliwinska-Kowalska, Grzanka & Zalewski, 2005).

Another limitation of the use of DPOAEs for a noise-exposed population relates specifically to the deep mining environment of the South African gold mining industry, namely the potential changes in middle ear pressure from descending into underground mines. Changes in middle ear pressure have been reported to reduce OAE amplitudes by between three and six dBSPLs (Clark, 2004). The effects of such reduced amplitudes must be taken into account for all populations but more especially when using the test method in the population of this study (de Koker et al., 2003) and high standards of outer and middle-ear evaluation must be applied before using DPOAEs and analysing the results (Habig, 2005; Franz & Schutte, 2005). Finally, a limitation of the use of DPOAEs in a noise-exposed population is that the same frequencies that are effected by noise (the higher frequencies) are also the frequencies where the expected normal amplitudes of emissions are reduced (Hall 2000:139) and may therefore result in the need for more complex analysis and interpretation of the results to differentiate between normal emissions and reduced or absent emissions.

4.4.1 DPOAEs and Temporary Threshold Shift (TTS)

TTS is caused by exposure to moderate-to-high levels of sound and is associated with changes in amplitude of DPOAEs (Lapsley Miller et al., 2006; Lutman & Hall, 2000). Recent animal studies suggest that a close relationship exists between the sound pressure level of the noise and the magnitude of the temporary emission shift (TES) as well as the recovery time of the TTS (Harding & Bohne, 2004). Histopathological changes as a result of exposure to noise levels below those commonly regarded as dangerous (85 dBA) were reported (Duvdevany & Furst, 2007) and may be an indication of the need to reevaluate the accepted occupational exposure limits (OELs), using the improved information provided by the use of DPOAEs.

In humans, studies concerning pre- and post-gunshot noise exposure and exposure to work-related noise, both with and without hearing protection, have confirmed the findings of the animal studies and have found that DPOAEs are more affected at 3 kHz (Balatsouras et al., 2005; Edwards & Taela, 2008; Olszewski, Milonski, Sulowski, Majak, & Olszewski, 2005). The response of post-shooting DPOAE supports the proposal that DPOAEs may be a fast, objective tool for performing monitoring of noise-exposed individuals (Balatsouras, 2004; Balatsouras et al., 2005; Seixas, Kujawa, Norton, Sheppard, Neitzel & Slee, 2004).

Authors have highlighted the value of the speed and cost effectiveness of the use of DPOAEs in a noise-exposed population (de Koker et al., 2003; Vinck, 1999). Models for the possible use of DPOAE screening criteria, as an alternative method in the annual medical surveillance procedure, have also been proposed (Balatsouras, 2004; Chan et al., 2004; Kim, Frisna, & Frisna, 2002). The use of the test to monitor the effectiveness of hearing protection devices has also been shown to be feasible (Bockstael et al., 2008; Hall & Lutman, 1999).

4.5 Prediction of Hearing Threshold Levels from DPOAEs

The objective nature of the DPOAE test means that there is a great deal of potential for providing a prediction tool for a difficult-to-test population. Such a tool would allow the clinician to use the objective test results to inform the management of clients, thereby excluding the need for a behavioural response from the client during testing. However, owing to the complex nature of both tests, DPOAE and the audiogram, proposed prediction models vary, depending on some or all of the following factors:

- the population for which the prediction model is developed, e.g. paediatric, adult, noise exposed;
- the method of testing used, e.g. Input/Output, screening, diagnostic; and
- the aspect of auditory function that the prediction provides, e.g. category of hearing loss or frequency-specific thresholds.

DPOAEs present with inherent limitations which have been shown in research reports to not be a reliable way of predicting thresholds for individual subjects. In addition to this the fact that they are absent at moderate to high degrees of hearing loss further limits the predicting hearing thresholds. Another limitation to the accurate prediction of hearing thresholds is the understanding that DPOAEs are not a measure of hearing but rather an indication of the status of the cochlea and the functioning of the OHCs (Hall, 2000:16). Furthermore, the use of DPOAEs as a basis of predicted hearing threshold levels in NIHL management is limited by legislation and regulations internationally that use the behavioural audiogram as the gold standard and basis for calculation of compensation claims. The fact that governmental, health, labour and monetary policies are developed over long periods of time with far reaching implications would make it very difficult to bring about change (DME, 1996; DME, 2003; Hall, 2000; Le Page & Murray, 1998).

However, this can be counter-argued with the proposal that the compensation given for hearing should be based on the amount of anatomical and functional damage to the organ used for hearing. Additionally, if research can provide the scientific proof that alternative methods are fairer and more efficient, then scientists are morally obliged to pursue the investigation. Currently, DPOAEs are used primarily as a cross-check for the audiogram and in South African legislation DPOAE use is not mentioned nor taken into account in compensation claims (COIDA, 1993; DME, 1996; DME, 2003). There is clearly a need to inform those policy makers that improvement of this policy can be attained to ensure fair compensation for all parties. Finally, the limitation to the possibility that DPOAE levels can predict hearing threshold levels may be due to the fact that any such predictive tool would need to be based on strong statistical correlations between the two types of results, and early research failed to show such correlations. However, more recent studies no longer question the relationship (Gorga et al., 1997; Hall, 2000).

4.5.1 Previously reported prediction of hearing thresholds from DPOAEs studies

Kimberley, Hernadi, Anva and Brown (1994) reported that in their study they established emission thresholds in a population that had been selected without regard for age, gender nor type or configuration of hearing loss, and found correlation coefficients of 0.86. Consequently, the prediction model allowed the prediction of auditory thresholds within 10dB of the actual thresholds. Their study described multivariate analyses that used a combination of DPOAE and other variables (such as age or gender) to predict hearing loss at specific frequencies. The study found no improvement in the test performance when multivariate techniques were used compared to a univariate approaches.

In contrast, Dorn et al. (1999) reported improvements in test performance when multivariate analyses were applied to DPOAE data that included several variables namely DPOAE, DPOAE/Noise, discriminant function (DF) scores and logit function (LF) scores. In their study over 1200 normal-hearing and hearing-impaired ears were used with hearing levels ranging from 5dB to greater than

120 dBHL and the data from these ears were divided into two groups, a training group on which the multivariate solutions were developed and a second group on which the prediction model was validated. They reported that multivariate analyses resulted in better predictions than for either DPOAE level or SNR alone. The improvements in test performance were greatest for frequencies at which the univariate techniques performed the poorest (0.75, 1, 1.5, and 8 kHz). The multivariate solutions proved to be as successful in predicting when applied to the validation group and therefore showed that the method could be generalised to other populations.

In two studies by Gorga, Neely, Ohlrich, Hoover, Redner & Peter (1997) and Gorga, Neely & Dorn (1999) it was shown that when using commercially available equipment in a typical test environment that was quiet, but not sound-treated, that the distinction between normal and impaired ears could be accurately predicted. The prediction was on the basis of categories of the degree of hearing loss. The sample size used in 1999 study was 1267 ears that had ruled out the influence of middle ear abnormality and measured DPOAEs between 750Hz and 8000Hz, at levels of 65 dBSPL and 55 dBSPL. The reported goal of the multivariate analyses used was to achieve the greatest separation between the distributions of responses from normal and impaired ears. Several input variables (e.g. DPOAE signal and noise levels at several frequencies) were used to create a new dimensionless variable (the LF score). This dimensionless variable represents a linear combination of the input variables, each of which is multiplied by a coefficient. The specific variables and their associated coefficients are chosen so that, along the new dimensionless variable (LF score), maximum separation is achieved between the distributions of responses from normal and impaired ears (Gorga et al., 2005).

The purpose of the Gorga et al. (2005) study was to further evaluate the multivariate solutions described in Dorn et al. (1999) and Gorga et al. (1999), using DPOAE data collected on an entirely new set of ears using equipment that differed in several ways from the equipment used by Dorn et al. and Gorga et al. The aim was to evaluate how robust and universal the prediction model was and therefore their clinical use. They found that the prediction model for the category of hearing loss could be generalised successfully to other data sets and that the prediction was best at f_2=5KHz and f_2=6KHz. (Gorga et al., 2005)

De Waal (2000) developed an automated neural network by training the computerised programme to evaluate the different aspects of DPOAE measurements. The study aimed to predict categories of hearing levels of 10dB steps. The success of the prediction was mixed but the author felt that this was due to too few subjects with which to train the neural network.

The increasing understanding that a relationship exists between DPOAEs and hearing threshold levels has developed as a result of the growing awareness of the fine structure of DPOAEs (the stimulus intensity and frequency, the emission signal analysis, and the statistical analysis of data) (Dhar et al., 2002; Dhar et al., 2005; Franklin et al., 1992; Harrison, Sharma, Brown, Jiwani, & James, 2008; He et al., 2007; Johnson et al., 2006; Johnson, Neely, Kopun, Dierking, Tan, Converse et al., 2007; Martin et al., 1998; Namyslowski et al., 2001; Neely, Johnson, Garner, & Gorga, 2005). The multitude of varieties of stimulus combinations for both frequency and intensity and the many possible ways in which the signal measured in the outer ear can be processed as well as the multifaceted ways of statistically analysing these measurements for prediction purposes all result in a very complex debate with many possible conclusions.

4.5.2 Correlation with Air-conduction Hearing Threshold Levels

A prerequisite of a prediction model of hearing threshold levels from DPOAEs is the need to show a correlation between the two test results. Researchers have investigated the correlation between the DPOAE levels and the air-conduction hearing threshold levels and have concluded:

- there is a correlation between hearing threshold levels and DPOAE levels in a curvilinear-shaped relationship with a moderate degree of linearity (Dorn et al., 1999; Gorga et al., 2000; Gorga, Dierking, Johnson, Beauchaine, Garner & Neely, 2005); and

- there is a mid- and high-frequency correlation with low- and extra-high (above 8 kHz) frequencies being less strongly correlated (Dorn et al., 1999; Gorga et al., 2005).

When using the I/O method of eliciting an emission, correlations of r=0.65 p<0.001 for I/O thresholds and hearing thresholds have been shown (Boege & Janssen, 2002; Goldman, Sheppard, Kujawa, & Seixas, 2006; Nielschalk, Hustert, & Stoll, 1998). TEOAEs were found to separate ears with normal hearing from those with hearing loss reliably, using a variety of stimulus and response conditions in children (Harrison & Norton, 1999) and correlations ranging from r=0.644 to 0.89 (p < 0.001) between hearing threshold levels and TEOAE were reported (Avan & Bonfils, 2005). In contrast, poor correlations between TEOAEs and behavioural audiograms in noise-exposed populations have also been reported (de Koker et al., 2003).

In contrast to the other forms of OAEs and their relationship to hearing threshold levels, the emission level of DPOAEs has been shown to categorise normal and impaired hearing threshold levels for low- and high-frequencies reliably, but to have weaker correlations at mid-frequencies (Gorga et al., 1997). The reported correlations between DPOAE levels and hearing threshold levels vary according to the method used in measurement and the nature of the study population. Some of the reported correlations are:

- between I/O DPOAE threshold and pure-tone threshold: r = 0.65, (p<0.001) (Boege & Janssen, 2002);
- between DPOAEs at the corresponding frequencies and audiogram frequencies: r =-0.22 at 6 kHz ranging to a maximum of r =-0.38 at 4 kHz (p <0.01) (Attias, Horovitz, El-Hatib, & Nageris, 2001);
- in an unscreened adult population: the range is between r =-0.541 and r = -0.738 (Engdahl et al., 2005); and
- in a noise-exposed population: the range is between r = -0.56 for 1 kHz and r =-0.61 for 4 khz (p<0.05) (Vinck, 1999).

The correlations between the two test measurements have laid the foundations for the development of prediction models. Researchers have proposed prediction models using OAEs to determine hearing sensitivity with varying success (de Waal, Hugo, Soer, & Krüger, 2002; Dorn et al., 1999; Gorga et al., 2000; Ma & Zhang, 1999; Seixas et al., 2004; Shaffer & Dhar, 2006).

OAEs have been used to predict hearing sensitivity by determining the cut-off hearing levels that are associated with the presence or absence of an OAE response (de Waal et al., 2002; Dorn et al., 1999). Input/Output functions have been shown to predict hearing threshold levels for both normal and hearing-impaired ears reliably. In noise-exposed subjects the I/O curves diminish most in the 3 – 4 KHz frequency range, confirming the NIHL pattern (Boege & Janssen, 2002; Goldman et al., 2006; Hall, 2000). Some research proposes the use of a combination of DPOAEs and TEOAEs to improve the prediction ability of the auditory status (Dhar et al., 2005; Dorn et al., 1998; Engdahl & Kemp, 1998; Le Page & Murray, 1998).

Earlier research used univariate analysis with less accuracy while the use of a multivariate analysis or combined multiple predictor variables on large sample sizes covering the full age range and the full range of thresholds has yielded high predictive abilities that have been validated on independent data (Dorn et al., 1999). Both composite and component analyses of DPOAEs have revealed equal abilities to predict the auditory thresholds and degree of hearing loss (Dorn et al., 1999). The emission closest to f_2=6 KHz was found to contribute significantly to the prediction of all frequencies (Dorn et al., 1999).

4.5.3 Averages of DPOAE Levels

In an effort to further evaluate test-performance improvements with multivariate analyses, Gorga et al. (1999) evaluated DPOAE test performance when the "gold standards" were based on audiometric thresholds for groups of frequencies. Each group of frequencies was selected because of their potential to be included in screening applications of the DPOAE test. Several multi-frequency gold-standard definitions were used, including pure-tone averages (simple arithmetic averages across several frequencies) and extrema thresholds (in which extra weight was given to frequencies for which thresholds were particularly elevated). Just as in the single-frequency case, test performance improved when multivariate analyses of DPOAE data were used to predict audiometric status based on multi-frequency gold standards. Interestingly, there was little difference in performance among pure-tone average, extrema, or a combination of average and extrema gold standards.

Pure-tone averages are used as standard practice in behavioural audiometry and, as discussed in Chapter Two, are used as a cross-check on the reliability of audiometric pure-tone test results. The clinical use of DPOAEs is not mature enough yet for many reports of an averaged DPOAE measure for similar purposes. However, studies have compared the prediction abilities of univariate DPOAE measures with the multivariate or averaged combination of DPOAE levels (Dorn et al., 1999; Gorga et al., 1999; Gorga et al., 2000; Gorga et al., 2005). The averaging of emission levels was reported to reduce variability and increase the correlation and the ability to predict hearing threshold levels from DPOAEs (Dorn et al., 1999; Gorga et al., 2000; Gorga et al., 2005). The large database in the current study provided the opportunity to investigate the averaging method further. Results of the investigation can potentially inform the development of a “Cochlea Function Average” as a clinical tool which could be used in screening methods or as an overall index of cochlea function.

4.5.4 Speech Recognition Thresholds (SRTs) and DPOAEs

The discussion in Chapter Two on NIHL also highlights the fact that confirming the reliability of hearing threshold levels is an integral part of diagnostic audiology and that the cross-check principle is an accepted principle in audiology practice (Turner, 2003). The cross-check concept means that one test result confirms another test result and requires agreement between both tests before a diagnostic decision can be made (Turner, 2003). The use of a cross-check between an SRT and a DPOAE level has not been previously investigated and requires further investigation to extend the body of knowledge regarding how the use of the DPOAE objective test interacts with other test results in a test battery. Despite the weak correlation between SRT and PTA in sloping hearing losses (Picard et al., 1999) the configuration of NIHL losses usually has normal to mild losses in the lower frequencies (500Hz, 1000Hz and 2000Hz) which are the frequencies used to calculate the PTA. Therefore if a correlation between SRT and averaged DPOAE in the lower frequencies could be shown to exist, a valuable clinical tool could be provided, namely an objective cross-check test enhancing the diagnostic decision for NIHL compensation.

4.6 Conclusion

The proliferation of recent research on DPOAEs and their use as a predictor of hearing threshold levels (Gorga et al., 1997; Lapsley Miller & Marshall, 2001; Lucertini et al., 2002; Marshall et al., 2001; Ricci, Molini, Alunni, Galluci, Quaglietti & Cerquetti, 1999; Sliwinska-Kowalska & Kotylo, 1997) as well as the estimated 30% of claimants who exaggerate their hearing threshold for compensation reasons (Le Page & Murray, 1998) is evidence of the need for improved knowledge about the objective DPOAE test that will improve the audiologist and hearing health team members to use DPOAEs with more confidence and more effectivley. The confidence that such answers would provide would be particularly useful for difficult-to-test clients such as in the case of pseudohypacusis or in the case where language and culture differences between the tester and the client confound the reliability of results. The current study aimed to build on the existing knowledge about NIHL and DPOAEs by investigating the characteristics of DPOAEs and their correlations with hearing threshold levels. The study also proposed to develop a method of predicting hearing threshold levels from DPOAEs in a noise-exposed population. The predicted hearing threshold levels could then be used to calculate the PLH and the percentage of disability (PD) for the purpose of compensation for NIHL.