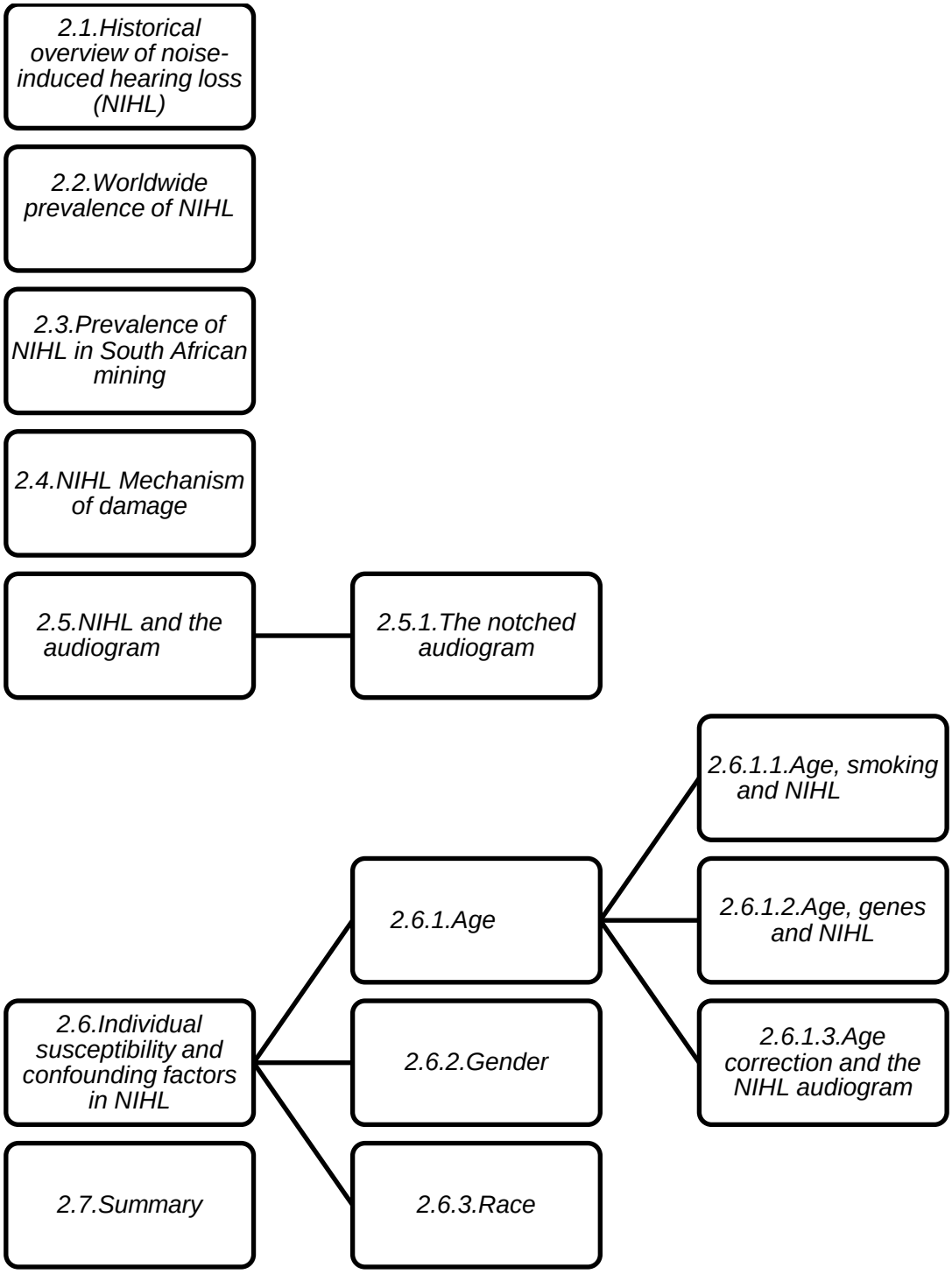
## 2. Noise-induced hearing loss: Overview



The following scheme outlines the literature review that was followed in Chapter 2 and 3:

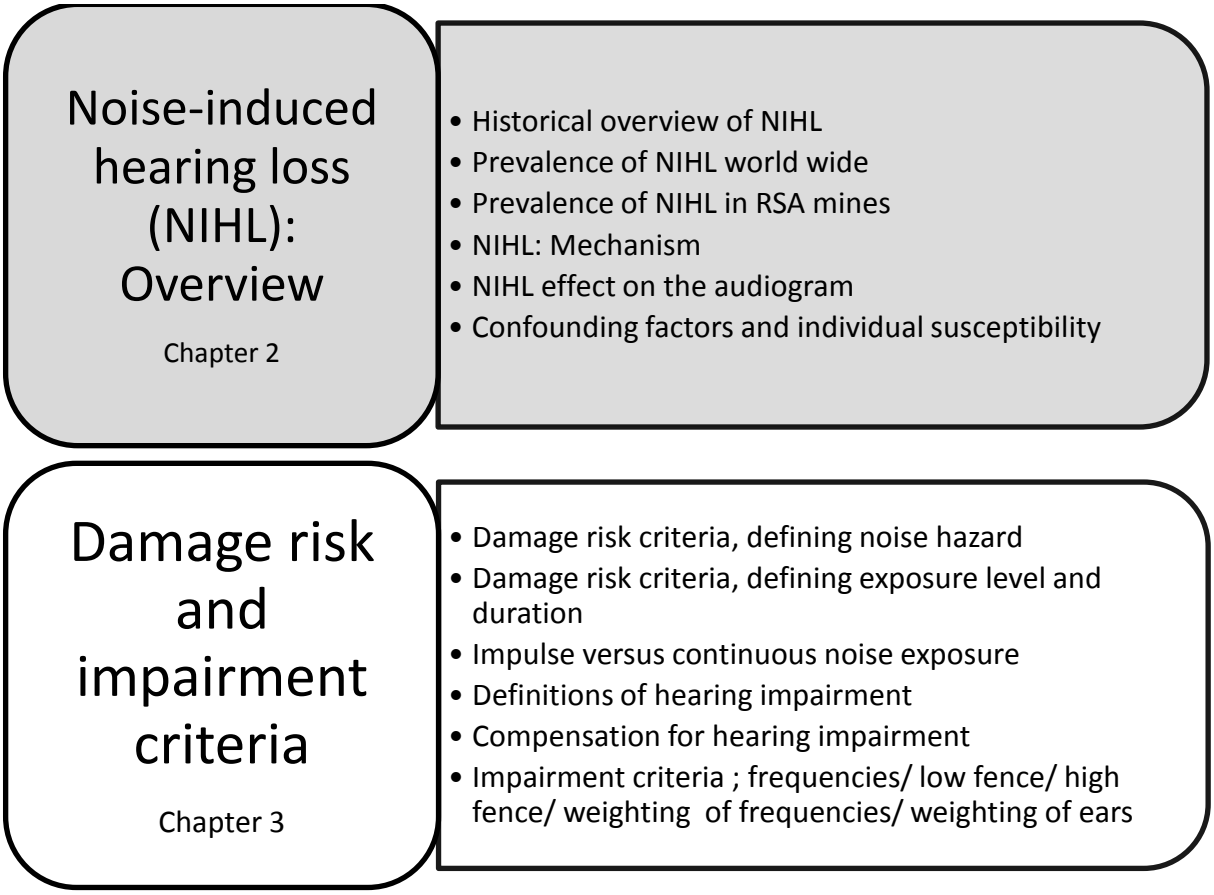



**Figure 2-1 Outline of literature review followed in chapters two and three**

## 2.1. Historical overview of noise-induced hearing loss (NIHL)

For the audiologist hearing loss caused by noise has a special significance as the profession of audiology owes its origin to hearing loss caused by war-related blasts and gunfire (Clark, 2000). Excessive noise has always been associated with firearms, ammunition and wars. Centuries ago noise-induced hearing loss (NIHL) was first documented by a French surgeon, Ambroise Paré (1510-1590), when he described the treatment of injuries sustained by firearms (McIlwain, Gates, & Ciliax, 2008). According to the medical records of United States Army (USA) (McIlwain, Gates, & Ciliax, 2008) many soldiers were diagnosed with hearing loss after World War I. It was only after the Second World War in 1945, however, that the profession of audiology was born to address the great need for intervention after many soldiers

had sustained hearing loss. After this life-altering war, the terms “audiology” and “audiologist” were used for the first time (Berger, 1976; Jerger, 2009).

Loud noise, however, is not only associated with wars and ammunition. As the effects of the Industrial Revolution spread throughout Western Europe and North America during the 19th century many changes were made to methods of work by the introduction of machinery (Deanne, 2000). Hazardous noise in the workplace was an inevitable consequence. The introduction of steam power relating to the industrial revolution first brought attention to noise as an occupational hazard (NIOSH, 1998). Craftsmen who fabricated steam boilers developed hearing loss in such numbers that the resultant impairment was referred to as “boilermaker’s disease” (Clark, 2000; NIOSH, 1998). The recognition of “boilermaker's disease” has been referred to in literature as one of the major historical events in the relating of noise-induced hearing loss to noise exposure (Johnson, 1999). The devastating effect of noise on hearing has since multiplied in most trades and all industries as a result of increasing mechanisation.

Mining is yet another trade strongly associated with excessive noise. Mining minerals has always been a gruelling, forceful task both underground and on the surface. As early as the first century BC Diodorius Siculus (Greek historian; 1st century BC (Agricola, 1950) ) describes the process of mining: *“The physically strongest break the rock with iron hammers, applying no skill to the task, but only force”* (Agricola, 1950, p. 280). Drilling shot holes was one of the first mining operations to become mechanised (McBride, 2004). Today the pneumatic percussion drill is still regarded as one of the major noise hazards in mining (McBride, 2004).

In the early years audiologists focused mainly on the treatment of NIHL. Since then the focus has shifted from intervention to prevention of NIHL. Although the measurement of hearing loss was possible prior to 1940 it was not until 1937 that actual reports of hearing measurements were made of persons with NIHL (Glorig, 1980). A group in the Armed Forces of the USA gave research momentum when a working group was formed in 1953 to study the effects of high intensity noise on the human body (Mcllwain, Gates, & Ciliax, 2008). This study was called the Biological Effects of Noise Exploratory Study (BENOX Report) and it became the first report to recommend monitoring for the prevention of NIHL as well as the establishment of a

database to track hearing loss (Johnson, 1999; McIlwain, Gates, & Ciliax, 2008). As a result of the BENOX Report and the wide distribution of its results, prevention was considered the best solution to noise-induced hearing loss.

The American Academy of Otology and Otolaryngology published the first written guide on hearing conservation outside of the military in 1953. Hearing conservation can be defined in a broad sense as the preservation of normal and residual hearing (Glorig, 1980). In the United States the federal government included a noise standard in the Occupational Health and Safety Act of 1972 (Sataloff & Sataloff, 2006). This standard made it mandatory for industries to reduce noise by every feasible means where employees are exposed to harmful noise. If the noise cannot be reduced adequately a hearing conservation programme has to be established. In 1979 the US Department of Labor regulated the elements of a hearing conservation programme which included guidelines and forced industrial compliance (Sataloff & Sataloff, 2006).

The shifting of the focus to prevention of NIHL through regulations and hearing conservation programmes soon spread from the United States to other countries around the globe. In the United Kingdom a joint investigation by the Medical Research Council and the National Physical Laboratory established the relationship between noise exposure and hearing loss and defined data regarding noise levels and duration of noise exposure with consequent hearing loss (Flood, 1987). The results from these studies led to a Code of Practice published by the Department of Employment (UK) in 1972. Although this code was an advisory document, a breach of this code was admissible as evidence of negligence and breach of statutory duty (Uddin, Dingle, Sharp, & Flood, 2006).

In 1981 the Occupational Safety and Health Association (OSHA[4]), who is the main US federal agency charged with the enforcement of safety and health legislation, created hearing conservation standards for employees exposed to excessive noise (US Department of Labor, 1983). The standards specified the permissible sound levels and duration of noise exposure and also mandated hearing conservation

[4] OSHA: The United States Occupational Safety and Health Administration (OSHA) is an agency of the United States Department of Labor with the mission to prevent work-related injuries, illnesses, and occupational fatality by issuing and enforcing standards for workplace safety and health (retrieved from http://www.osha.gov/comp-links.html on March 08, 2011).

programmes (HCP) for workers exposed to excessive noise (US Department of Labor, 1983).

Shortly thereafter NIHL in South African gold miners was reported in the medical literature (Hessel & Sluis-Cremer, 1987). In 1988, soon after this publication, the South African Chamber of Mines published guidelines for the implementation and control of an HCP in the mining industry (COMRO, 1988). In 1996 the components of HCPs were included in the Mine Health and Safety Act (Department of Minerals and Energy, 1996).

## 2.2. Worldwide prevalence of NIHL

Even with the shift in emphasis from treatment to prevention and the worldwide implementation of hearing conservation programmes, hearing loss caused by noise is still prevalent (SANS10083:2004, 2004). A study commissioned by the World Health Organisation (WHO) evaluated the worldwide status quo of occupational noise exposure and resultant hearing loss (Nelson, et al., 2005a). This comparative risk assessment was done as part of the WHO's on going Global Burden of Disease (GBD)[5] project.

The assessment estimates the global burden[6] of disease and injuries resulting from risk factors including NIHL (Nelson, et al., 2005). According to this study, the WHO estimates indicate that a large percentage of disabling hearing loss in adults worldwide is attributable to occupational noise (Nelson, et al., 2005a). Nelson and colleagues (2005) give account of 17 studies conducted in 12 countries where high occupational noise exposure levels were reported. These high noise levels occurred

[5] The WHO GBD measures burden of disease using the disability-adjusted life year (DALY). This time-based measure combines years of life lost due to time lived in states of less than full health. The DALY metric was developed in the original GBD 1990 study to assess the burden of disease consistently across diseases, risk factors, and regions. In summary the GBD provides estimates of mortality and morbidity for causes of disease and injury (WHO, Global Burden of Disease, 2009).

[6] The term "burden" is a term typically used by population studies to refer to the effects of hearing loss. These effects, primarily on speech communication, and secondarily on social, emotional, and other domains of functioning, have often been subsumed under terms such as handicap, impairment, and disability (Dobie, 2008).

in a wide range of workplaces, including manufacturers of foods, fabrics, printed materials, metal products, drugs, watches, and in mining. Using noise exposure data from the US National Institute for Occupational Safety and Health (NIOSH), adjusted by data on the distribution of the workforce by occupational category and economic sector, and economic activity rates in each WHO subregion, the results indicated that occupational noise is an important risk factor for hearing loss in workers at most ages. Prevalence of NIHL range from 7% to 21% (averaging 16%) of the adult-onset hearing loss around the world (Nelson, et al., 2005a). Results indicate that the burden is more profound for certain occupations such as mining, and for males compared to females. Furthermore the burden is more significant in the developing world. It is estimated that 18% of adult-onset hearing losses in the 20 southern most countries in Africa (AFR-E region), including South Africa, are due to occupational noise exposure (Nelson, et al., 2005a).

Dobie (2008) provided a critical appraisal of the WHO study (Nelson, et al., 2005a). Dobie (2008) was part of a study estimating the contribution of aging and noise as causes of adult-onset hearing loss in the United States. The author questioned methodological aspects related to the WHO study (Nelson, et al., 2005a). In the risk assessments, for example, different hearing loss definitions were combined in a single model and age weighting was used. In this study a model of the hearing loss burden in American adults was constructed using data from the Census Bureau, from an international standard that predicts age-related and noise-induced hearing loss (ISO 1990:1999), from the American Medical Association's method of determining hearing impairment, and from sources estimating the distribution of occupational noise exposure in different age and sex groups (Dobie, 2008). Despite the differences in methodology, results from both studies estimate a similar burden of occupational NIHL. Dobie (2008) estimated that 10,5% of adults with moderate hearing loss in North America may be attributed to occupational noise, very similar to the WHO estimate of 9%. Results from both studies revealed that the risk peaked in middle age (45 to 59) (Dobie, 2008; Nelson, et al., 2005a). Regarding the higher WHO estimate for the burden of NIHL in developing countries (such as South Africa, 18%) versus developed countries (North America, 9%) Dobie and colleagues argue that these results can be supported by the fact that as manufacturing leaves

countries like the United States, developing countries have an *"ever-increasing share of the world's noisy jobs"* (Dobie, 2008, p. 574).

Both these studies thus confirm that a large proportion of adult-onset hearing loss can be attributed to occupational noise. Some factors might lead to an underestimate of the burden of NIHL. Prevalence studies in occupational diseases, such as NIHL, might for example be hampered by the fact that there is often an extended lead time for the disease to develop (Scott, Grayson, & Metz, 2004). If hearing is not tested frequently, NIHL might be underreported as figure 1 demonstrates. Due to this latency period of many occupational diseases, symptoms often present after a worker had left a workplace and thus go unidentified (Hermanus, 2006).

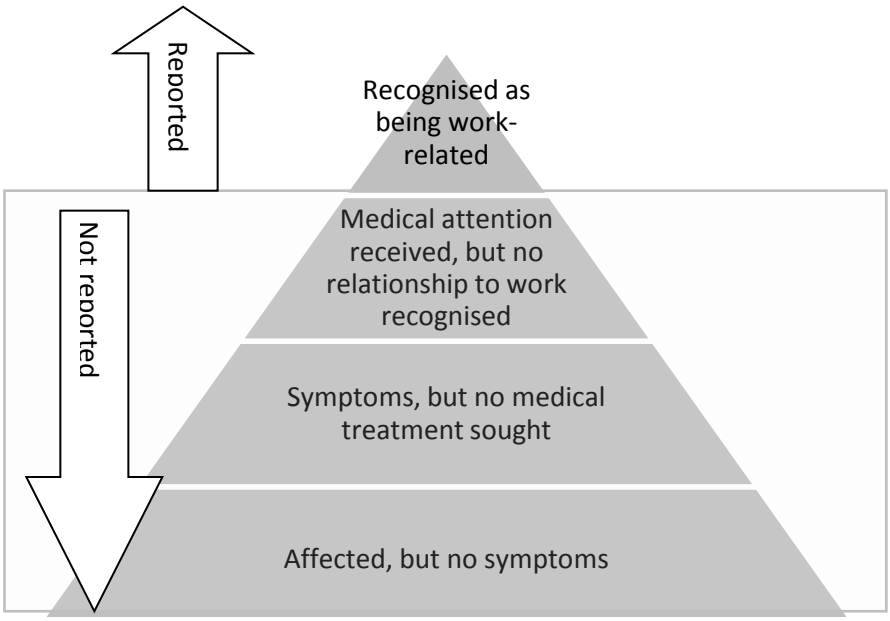



**Figure 2-2 Underreporting of occupational diseases. Source: Scott, Grayson, & Metz (2004)**

## 2.3. Prevalence of NIHL in South African mining

Mining as an occupation was identified in the WHO GBD study as an economic sector with a heavy burden of NIHL (Nelson, et al., 2005a). South Africa has a particularly large share of "noisy jobs" since the country has a large mining industry. The South African mining industry employs 5,1% of all workers in the non-agricultural, formal sectors of the economy, a reported total of 458 600 employees in

2006 (Mwape, et al., 2007). Results from a population- based study done by the National Institute of Occupational Safety and Health (NIOSH, 1998), referenced by Nelson and colleagues, indicate that 85% of all production workers and labourers in mining (in the US) were exposed to excessive noise. A recent survey of noise in South African mines found exposure values for operators of production machinery and for personnel in close proximity to range between 95 and 110 dB A (Franz & Phillips, 2001). It is estimated that 68 to 80% of mineworkers are exposed to dangerous noise levels, indicating a significant risk of hearing loss for the majority of the industry's personnel (Franz & Phillips, 2001).

A literature search reveals that no large scale prevalence studies have been conducted on NIHL in the mining industry in South Africa. The bulk of published material has been in the form of case reports, pathology studies, and collections of statutory data with few prevalence or incidence studies. The data used in the WHO burden of disease study was collected by Hessel and Sluis-Cremer (1987). The hearing loss of a large cohort of white gold miners, who constitute a very small section of the workforce in the mining industry, were investigated. In a frank and revealing article by McCulloch (2005) about the history of South African research into occupational diseases it is described as tainted by political agendas. In the article the author describes how research into the devastating effects of asbestos was stifled because of fear that it might negatively impact the prosperous industry. According to the author, South African science in this area was rendered irrelevant on the international stage because of unethical research practices which also reflect on how the industry managed occupational and environmental diseases (McCulloch, 2005). Ironically the author describes how researchers working at the National Institute for Occupational Health (NCOH) in South Africa between 1970 and 1990, including Sluis-Cremer, who co-authored a landmark NIHL study (Hessel & Sluis-Cremer, 1987), eventually died because of asbestos poisoning after only a few visits to these mines despite scientific claims to the safety of mining practices (McCulloch, 2005). The impact of many discriminatory practices of South Africa's past, which were allowed by legislation, such as disproportionate compensation pay-outs and benefits to black and white miners, inferior housing, poor working conditions and a general neglect of health and safety, is still evident and unfolding (Hermanus, 2006).

The Leon Commission of Inquiry of 1994 is the most recent commission to examine occupational health and safety in the South African mining industry (Franz & Phillips, 2001). In terms of occupational health, and specifically NIHL, the Commission found that between 40 to 80% of workers involved in drilling operations have hearing loss after 10 years of exposure (Hermanus, 2006). Further evidence of the high prevalence of NIHL in South African mines is found in compensation payment data. Table 2 presents these results for the year 2004/2005. It is clear from the discussion that NIHL in South African mines are very prevalent and large-scale research into the incidence and prevalence of NIHL is necessary. An audit of the Department of Minerals and Energy in the RSA reported 1820 cases of NIHL in 2007 (Sonjica & Nogxina, 2008). The Chamber of Mines reported a positive downward trend in the number of NIHL cases since 2007 (Chamber of Mines, 2012). It is possible that reported NIHL cases could have been inflated soon after 2001 as baseline hearing testing was only mandated after 2001 per Instruction 171 (COIDA, 2001).

**Table 2-1 Compensation paid for NIHL in South African Mines**

| Year | Number of cases | Compensation paid |
|---|---|---|
| **1998** | 5 395 | R 68 113 616 |
| **1999** | 6 106 | R 72 321 385 |
| **2000** | 4 965 | R 65 004 865 |
| **2001** | 5 654 | R 88 259 410 |
| **2002** | 14 457 | R 102 308 555 |
| **2003** | 7 241 | R 52 213 637 |
| **2004** | 3 849 | R 77 067 521 |

Source: (RMA, 2005)

## 2.4. NIHL Mechanism of damage

Most hearing losses are associated with aging and excessive noise exposure without any other detectable ear disease (Dobie, 2001; Alberti, 2001). As hearing loss due to age is not preventable, prevention of NIHL (by noise level reduction, exposure reduction and the use of hearing protection) would in all probability do more to reduce the societal burden of hearing loss than medical and surgical treatment of all

other ear diseases combined (Dobie, 2001). Elevated noise levels may lead to a number of non-auditory adverse effects, including elevated blood pressure and sleep interference (EPA, 1973; Nelson & Schwela, 2001) and may also interfere with communications and performance in the workplace, thus contributing to the occurrence of accidents (Girard, et al., 2009; Picard, Girard, Simard, Larocque, Leroux, & Turcotte, 2008). The most obvious consequence of exposure to intense sound is the occurrence of temporary and permanent hearing loss (Saunders, Dear, & Schneider, 1985). The most serious of these effects is irreversible hearing impairment. More subtle are the underlying physiological and anatomical consequences. The mechanism of NIHL and research findings in this area will be explored in the following section.

Perception of sound depends on the conduction of mechanical sound energy through the ossicles of the middle ear to the hydraulic medium of the cochlea. Middle ear injury from noise is rare and can occur only with extremely high sound pressure levels (Dobie, 2001). Research on human cadaver tympanic membranes (TM) demonstrated that extreme sound pressures, equivalent to at least 180 dB SPL, need to be present to perforate the TM (Garth, 1994). TM perforations with conductive and sensorineural hearing loss are part of the clinical picture of acoustic trauma[7] but not of NIHL (Dobie, 2001). The effects of sudden, explosive peaks of impulse noise may cause substantial mechanical disruption of middle and inner ear structures (May, 2000).

NIHL, due to exposure to continuous noise at hazardous intensities, causes a sensorineural hearing loss that is slow to develop (McReynolds, 2005). Once the mechanical energy (a result of the movement of the tympanic membrane caused by the sound waves) from the middle ear reaches the cochlea, it is translated into neural afferent information by the hair cells of the organ of Corti within the spiral structure of the cochlea (May, 2000). Figure 2 is a schematic representation of the ear and cochlea as illustrated by Kurmis and Apps (2007). Figure 3 shows a cross section of the basilar membrane and sensory cells (outer and inner hair cells) of the cochlea.

[7] Gloric (1980) suggested that the term noise-induced hearing loss should describe the loss which is produced over a long period of time from exposure to long-term noise. A single incident, e.g., an explosion or a blow, that has caused the hearing loss, should be called acoustic trauma.

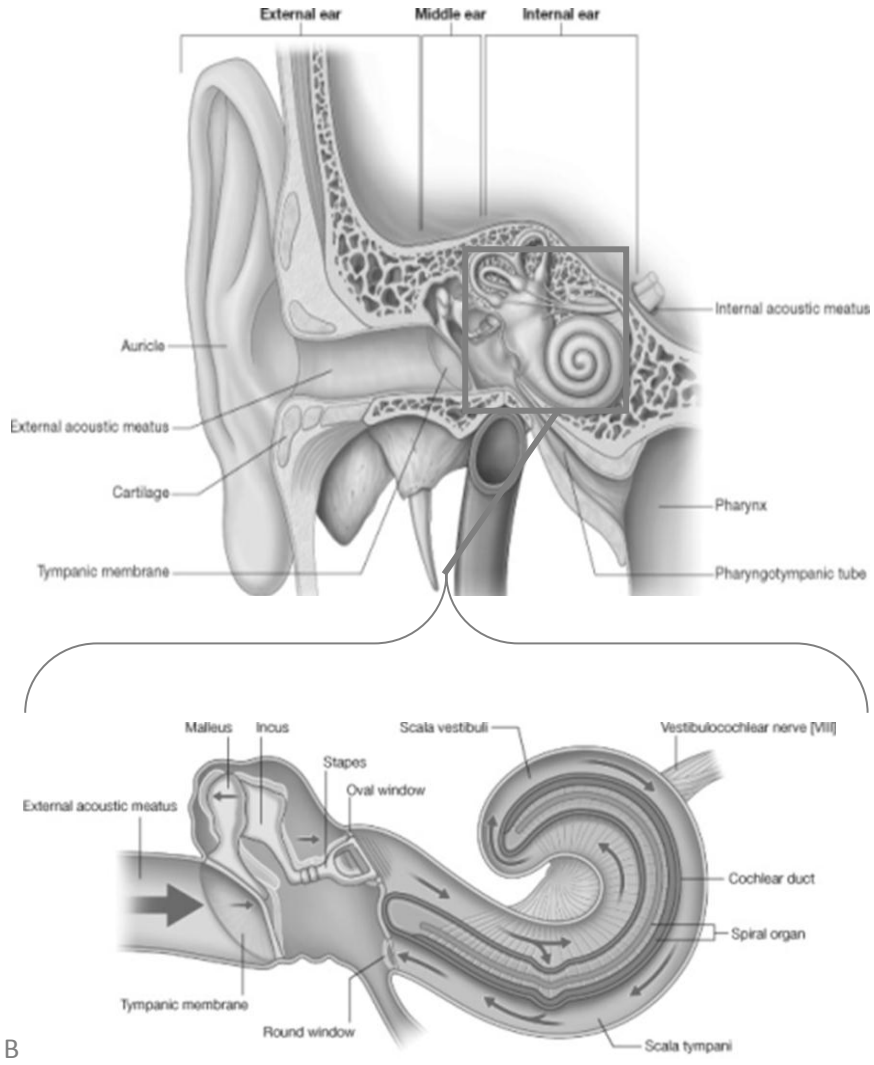



**Figure 2-3 (A) The ear and cochlea (B) Regions of the cochlea showing the sound conduction path. Source: Kurmis & Apps (2007)**

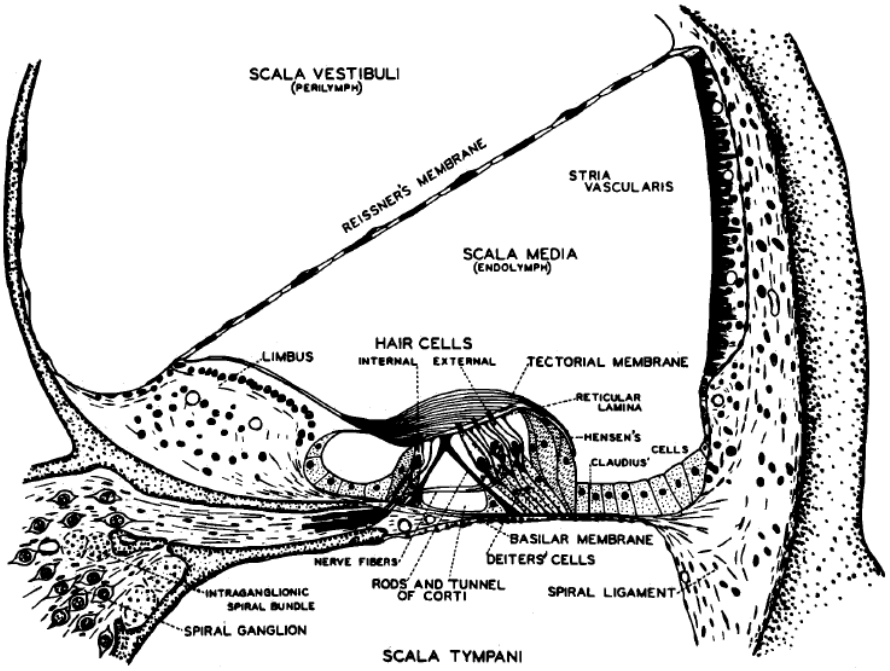



**Figure 2-4 Cross section of the basilar membrane showing sensory hair cells of the cochlea. Saunders, Dear, & Schneider (1985)**

Noise causes a broad set of physical changes in the major cellular systems in the cochlea. The most vulnerable structures in the cochlea are the outer hair cells (OHC) in the basal part of the cochlea. The basilar membrane is tonotopically organised with the lowest frequencies preferentially transduced at the apex and the highest frequencies at the base (Dobie, 2001). On the basilar membrane the OHCs in the area which responds to 4 kHz and the adjacent areas of 3 and 6 kHz are most susceptible to damage (Alberti, 2001; Kurmis & Apps, 2007). This is where the ear is most sensitive, in part because of the harmonic amplification of the ear canal and in part because of an unqualified sensitivity (Dobie, 2001; Alberti, 2001).

The inner hair cells (IHC) transfer signals via afferent neurons to the brain, whereas the vulnerable OHC act as a cochlear amplifier by enhancing the basilar membrane movements. Both types of hair cells possess a bundle of sensory hairs (stereocilia[8]) which react on sound stimulation by causing membrane depolarisation, neurotransmitter release and finally a generation of action potentials in the described attached cochlear nerves (Henderson, Bielefeld, Harris, & Hu, 2006). Changes to the stereocilia of the cochlear hair cells lead to diminished hearing sensitivity (based on hearing threshold testing) called a temporary threshold shift (TTS) and permanent

[8] Delicate hair-like structures, arranged in staggered rows on the apical surface of the sensory cells i.e. the inner and outer hair cells of the cochlea's basilar membrane (Alberti, 2001)

threshold shift (PTS) (Le Prell, et al., 2007; Henderson, et al., 2006; Dobie, 2001; May, 2000). There is a window of time between the disconnections of the tips of the largest stereocilia from the tectorial membrane in which the tips can reattach. TTS may partially be the consequence of the stereocilia damage and repair (Henderson & Hamernik, 1995). After initial exposure to hazardous noise the stereocilia lose their stiffness and consequently their ability to vibrate in response to sound and a reversible hearing loss is caused (TTS) (Dobie, 2001). After repeated hazardous exposures the stereocilia of the OHCs become permanently damaged (OHCs die) and a PTS (hearing loss) results. Damage to the OHC is greater than that of the IHCs presumably because OHCs experience a direct shearing force at their stereocilia, whereas the IHC stereocilia are stimulated by viscous drag. OHCs also have most of their long axis exposed to mechanical stress while IHCs have supporting cells on all surfaces. OHCs are furthermore closer to the point of maximum basilar membrane travelling wave displacement than the IHCs (Henderson & Hamernik, 1995).

Different pathways of hair cell death have been described. These investigations used cochlea dissection and histochemical methods for surface examination of chinchilla cochleae (Bohne, Harding, & Lee, 2006; Bohne, Zahn, & Bozzay, 1985; Gao, King, Zheng, Ruan, & Liu, 1992; Harding & Bohne, 2007; Harding, Bohne, & Vos, 2005; Henderson & Hamernik, 1995; Henderson, et al., 2006; Le Prell, et al., 2007; Kopke et al., 2005; Majno & Joris; 1995) . Investigators Majno and Joris (1995) stated that the term “necrosis” should be reserved for dead cells, regardless of which death pathway the cells had followed. A study by Bohne and colleagues (Bohne, Harding, & Lee, 2006), investigating the pathways of death for cochlear OHCs, report three possible pathways. These are:

1. *Oncotic* – swollen, pale-staining cell with a swollen nucleus;
2. *Apoptotic* – shrunken, dark-staining cell with a pyknotic nucleus; and
3. a *newly defined* third pathway – no basolateral plasma membrane but cellular debris arranged in the shape of an intact OHC with a nucleus deficient in nucleoplasm.

Previous experiments (Bohne, Zahn, & Bozzay, 1985; Henderson & Hamernik, 1995) reported that hair cells die for as many as 30 days after the hazardous noise exposure. Since OHCs die over a relatively long period, knowledge of the mechanisms of cell death may lead not only to methods of prevention but also to rescue after a hazardous noise exposure (Henderson, et al., 2006).

Recently, research on the cellular bases of NIHL has led to new avenues for protection through the use of prophylactic drugs (Henderson, et al., 2006). These research efforts have cast new light on the mechanism of NIHL (TTS and PTS) (Gao, et al., 1992; Kopke et al., 2005; Henderson, et al., 2006; Rabinowitz, Pierce Wise, Hur Mobo, Antonucci, Powell, & Slade, 2002; Le Prell, Yamashita, Minami, Yamasoba, & Miller, 2007). The hearing function of the cochlea not only depends on the structural integrity of the hair cells and surrounding support cells but also on the local vascular structures, and the immediate microenvironment (May, 2000). The following table summarises research findings in respect of the mechanism of NIHL.

**Table 2-2 Noise-induced hearing loss: Area of the cochlea where damage occurs, description of the mechanism of damage and illustrations**

| Cochlear area | Mechanism of NIHL |
|---|---|
| Structural integrity of the hair cells and surrounding support cells | • Noise can damage most of the cell populations in the cochlea, but the OHC are the most prominent pathological target (Henderson, et al., 2006).<br>• Because of noise stereocilia can be broken, fused, or have broken tip links that lead to loss of structural integrity (Henderson, et al., 2006; Saunders, Dear, Schneider, 1985).<br>• The ability of the stereocilia to act as mechanoelectrical transducers can also be reduced due to a loss of permeability of protein transduction channels in the cell membrane surrounding the stereocilia (Patuzzi, 2002).<br>• The tips of the stereocilia on outer hair cells (OHC) can be removed from their points of insertion into the tectorial membrane, leading to a loss of sensitivity (Henderson, et al., 2006; Gao et al., 1992; Alberti, 2001).<br>• Damage to pillar cells (supporting cell type) has also been observed after impulse noise and high-level continuous noise (115 dB SPL). The loss of the pillar cells interferes with the local impedance of vibration leading to a disruption of the mechanically coded vibration of the organ of Corti. In addition, the loss of the pillars may also contribute to the loss of OHC (Henderson & Hamernik, 1995; Henderson, et al., 2006).<br>• High-level noise can lead to acute swelling of the stria vascularis, swelling that is associated with loss of intermediate cells of the stria. The swelling disappears over time, but the loss of intermediate cells is permanent. Therefore, the overall size of the stria vascularis shrinks as a long-term result of noise exposure (Henderson, et al., 2006).<br>• Impulse noise exposures can damage the cochlea by causing direct mechanical damage. Depending on the intensity of the impulses, the organ of Corti can be ripped from the basilar membrane. Pillar and |

| Cochlear area | Mechanism of NIHL |
|---|---|
| | Hensen's cells can be destroyed, or their structural contributions in the organ of Corti can be compromised. In addition, cell junctions between HC, Deiters' cells, and Hensen's cells can be broken (Henderson & Hamernik, 1995;Henderson, et al., 2006).<br>• With more severe noise exposures, the pathology spreads to include IHC death (Henderson, et al., 2006). |

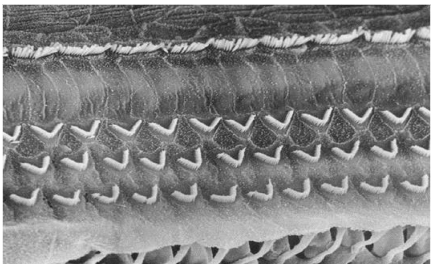


**Figure 2-5 Scanning electron micrograph showing the normal organisation of the organ of Corti. View is of the apical membrane of the single row of IHCs (top) and 3 rows of OHC (bottom). Notice the orderly arrangement of stereocilia (Picture retrieved from http://www.d.umn.edu/~jfitzake/Lectures/DMED/InnerEar/IEPathology/StereociliaDamage.html)**

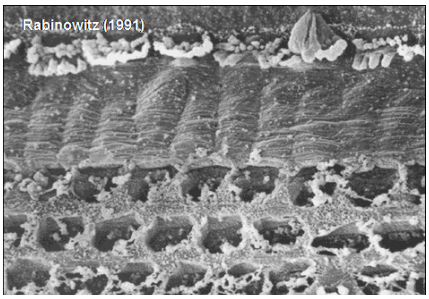



**Figure 2-6 Disruption of IHC stereocilia and loss of OHC in the basal turn of the cochlea following noise exposure (90 dB A noise for 8 hours) 6 months earlier. This damage produced a profound hearing loss (Picture retrieved from http://www.d.umn.edu/~jfitzake/Lectures/DMED/InnerEar/IEPathology/StereociliaDamage.html)**

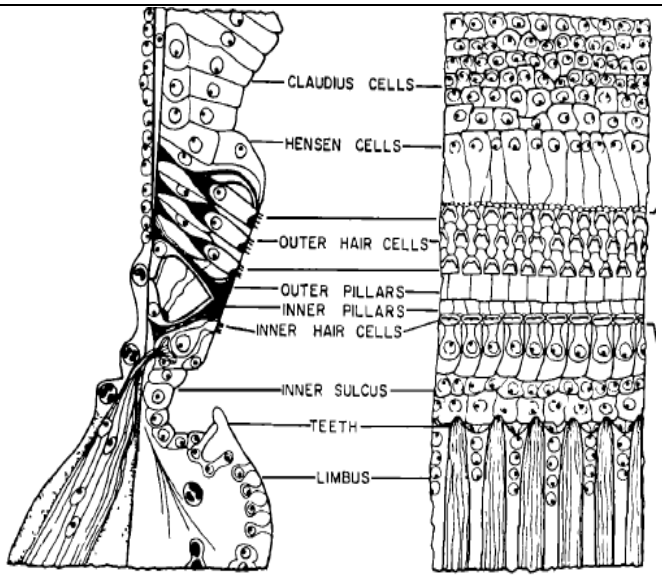



**Figure 2-7 A line drawing of the hair cells of the organ of Corti with a cross section view. Source: Saunders, Dear & Schneider (1985)**

| | |
|---|---|
| Local vascular structures and immediate microenvironment of the organ of Corti | • Factors such as leakage of extracellular fluid into the microenvironment and damage to support cells, vascular and neural structures may be playing a role in hearing loss secondary to loud noise (May, 2000).<br>• Partly associated with damage to the lateral wall blood vessels, high level noise exposure can reduce cochlear blood flow (CBF) (Henderson, et al., 2006).<br>• Other than the changes to the OHC structures another significant factor in the mechanism of NIHL is intense metabolic activity, which increases mitochondrial free radical formation (Kopke et al., 2005; Le Prell, et al., |

| Cochlear area | Mechanism of NIHL |
|---|---|
| | 2007).<br>• According to investigators Kopke and colleagues (2005) mitochondrial injury plays an important role in NIHL based on an assumed mechanism of cell death due to excessive reactive oxygen species (ROS) (and toxic free radicals) generation within the mitochondria. The balance between the production of ROS and the cellular anti-oxidants (AO) defence capacity determines the overall levels of ROS in living cells (Kopke et al., 2005; Henderson, et al., 2006; Rabinowitz, et al 2002). Evidence for a role of free radicals in NIHL and noise-induced sensory cell death is convincing, yet researchers are not clear whether the presence of ROS within noise-damaged cochlear tissue leads to cochlear damage or if the ROS are a product of damaged or dying cells (Henderson, et al., 2006; Kopke, et al., 2005; Le Prell, et al., 2007). The exact origins of the increased ROS observed in the cochlea are currently speculative (Henderson, et al., 2006).<br>• During high-level noise exposure, the IHC are highly active, leading to the release of large amounts of glutamate into the synapses with the type I fibres of the VIIIth nerve. The levels of glutamate in the synapses can overstimulate the glutamate receptors on the postsynaptic cells resulting in excitotoxicity, characterised by swelling of the postsynaptic cell bodies and dendrites (Henderson, et al., 2006; Sataloff & Sataloff, 2006). Over time, the swollen or ruptured dendrite terminals appear to recover and begin to function normally, suggesting that this type of damage may also contribute to TTS (Henderson, et al., 2006).<br>• With more severe noise exposures the pathology may include loss of auditory nerve fibres and damage to stria vascularis (Henderson, et al., 2006). |

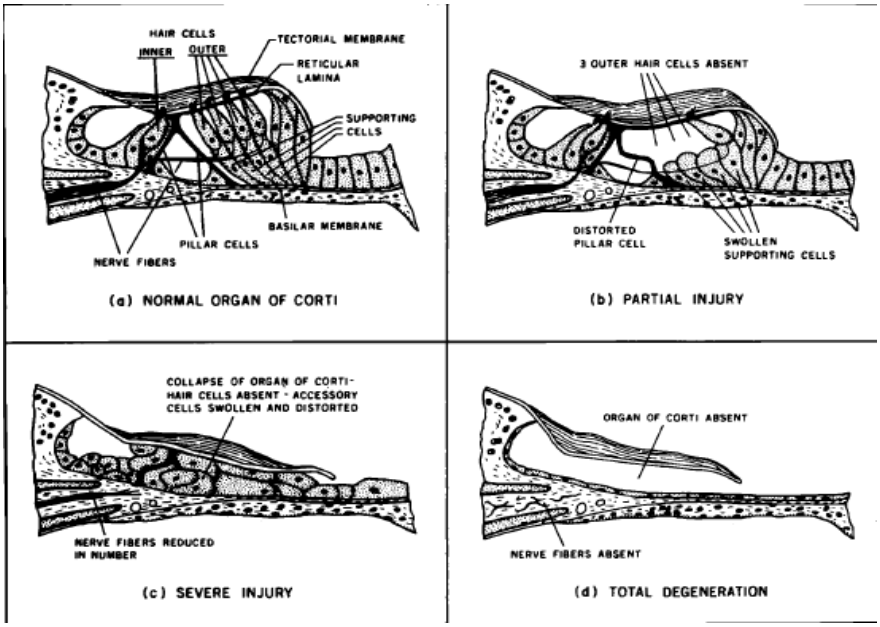



**Figure 2-8 Different levels of damage to the organ of Corti. Source: Saunders, Dear & Schneider (1985)**

Table 2.2 outlines areas of the cochlea that has shown damage or change in reaction to hazardous noise exposure. However, animal studies have repeatedly demonstrated that the relationship of these types of changes in the cochlea to decreases in hearing acuity is, at best, indirect (Henderson & Hamernik, 1995).

Factors such as leakage of extracellular fluid into the microenvironment, damage to support cells, vascular and neural structures as well as free radicals which may lead to cell death might be playing a role in hearing loss secondary to loud noise (as outlined in table 2.2). Based on the morphological appearance of combined focal lesions of different sizes, investigators Harding and Bohne (2007) conclude that many of the cochlear lesions due to excessive noise begin as pure OHC focal lesions, but with time, more OHCs in the area become injured and die, followed by pillar cells and IHCs.

It is noteworthy that the mechanism of damage to the cochlea differs depending on the nature of the damaging sound. Studies by Harding and Bohne (2007 & 2009) investigated the effect of a high-frequency pure tone (4 kHz) and a low-frequency pure tone (0,5 kHz) on the cochlea. For both pure tones, OHC focal lesions and combined focal lesions had substantially larger sizes than IHC focal lesions and the OHC lesions were almost twice as large in cochleae exposed to the 4 kHz pure tone compared to those exposed to the 0,5 kHz tone. On the other hand, IHC focal lesions had similar sizes, regardless of the exposure pure tone (Harding & Bohne, 2009). Two studies by Bohne and colleagues investigated whether the magnitude and pattern of cochlear damage is altered when exposure to noise is interrupted by regularly spaced rest periods (Bohne, Zahn, & Bozzay, 1985; Harding & Bohne, 2009). Rest has been shown to be protective for noise-induced hair-cell loss in general (Bohne, Zahn, & Bozzay, 1985). The results showed that rest periods during the exposure to damaging noise substantially reduced the development of focal lesions in the basal half of the organ of Corti from high-frequency noise (e.g., a 4-kHz pure tone). Also, rest reduced the formation of focal lesions in the apical half from a low-frequency noise (e.g., a 0,5 kHz pure tone). However, rest only partially protected the exposed chinchilla cochleae against the formation of focal lesions in the basal half of the organ of Corti for a damaging low frequency pure tone (Harding & Bohne, 2009). There was thus considerable less damage to the cochlea apex regions (low frequencies) when low-frequency sounds were made intermittent with the same total sound energy than in the basal area (Bohne, Zahn, & Bozzay, 1985). These observations lead the investigators to support the notion that the mechanisms for the development of focal lesions in particular, and hair-cell loss in general, differ in the basal and apical halves of the organ of Corti.

## 2.5. NIHL and the audiogram

NIHL causes a sensorineural hearing loss which is typically bilateral (American College of Occupational and Environmental Medicine (ACOEM), 2003). Asymmetric sources of noise, such as sirens or gunshots, can produce asymmetric loss (ACOEM, 2003). Because of the tonotopical organisation of the cochlea (with the lowest frequencies preferentially transduced at the apex and the highest frequencies at the base) one might expect an intense pure tone to damage the cochlear region that best transduces the tone to cause a hearing loss for the frequency of the stimulating tone. The maximum loss for pure tone exposure is estimated however to be approximately a half-octave above the offending frequency (e.g. 1 kHz tone will cause damage at 1,5 kHz) (Harding, et al., 2005; Dobie, 2001; Saunders, Cohen, & Szymko, 1991). This is where the greatest loss of hair cells occurs, near the upper edge of the exposure band (Harding & Bohne, 2007; Harding, et al., 2005). As explored in the previous section low-frequency sounds can also damage the high-frequency part of the cochlea (Dobie, 2001; Bohne, Zahn, & Bozzay, 1985; Bohne, Harding, & Lee, 2006). In chinchilla cochleae exposed to a 4 kHz pure tone, lesions were distributed throughout the basal half of the cochlea. In cochleae exposed to the 0,5 kHz tone, lesions occurred in the basal (high- frequency) and apical (low-frequency) area of the cochlea (Harding & Bohne, 2009). But considering the nature of noise exposure in the workplace, occupational noise is seldom centred around a specific pure tone. It is mostly broadband in nature and is defined by weighted measurements that are indicative of the response of the hearing mechanism (NIOSH, 1972). This weighted scale of noise measurement and noise hazard will be discussed in chapter three. In the following paragraphs the effect of occupational noise exposure on the audiogram will be discussed.

### 2.5.1. The notched audiogram

Broadband noise can cause widespread damage to the cochlea but the basal part of the cochlea shows the greatest changes, especially the 3 to 6 kHz area (Dobie, 2001). A notch in the audiogram greatest at 4 kHz has been known to be associated

with excessive exposure to noise for more than a century (Clark, 2000; Harding & Bohne, 2009).In an 1860 textbook, Toynbee noted a decrease in hearing of the 5 octaves tuning fork, with a characteristic frequency of 4096 Hz, by patients who engaged in the hobby of sport shooting (Toynbee, 1860). This loss was also termed the "C5 dip" until the 1930s when audiometers and pure tone audiometry were available and the "4 kHz" classification was adopted (Clark, 2000). Despite the early recognition of the typical NIHL audiogram pattern, the progression of this loss was first studied systematically in cross sectional studies in a cross section of general workplaces in England and Wales (NIOSH, 1972; McBride, 2004). These results confirmed that with exposure to broad band, steady noise, or noise with an impulsive component, the first sign was a dip or notch in the audiogram greatest at 4 kHz with recovery at 6 and 8 kHz with an overall audiogram shape concave upward (Rabinowitz, et al 2006; NIOSH, 1972). Audiograms show a pattern which is usually bilateral and shows a typical “notch” in the 4 kHz range on the audiogram (Figure 8). As the loss proceeds, the notch becomes deeper and broader, extending toward both the 2 kHz and the 8 kHz range as it begins to seriously affect speech discrimination (May, 2000). This typical notch audiogram is shown in figure 8.

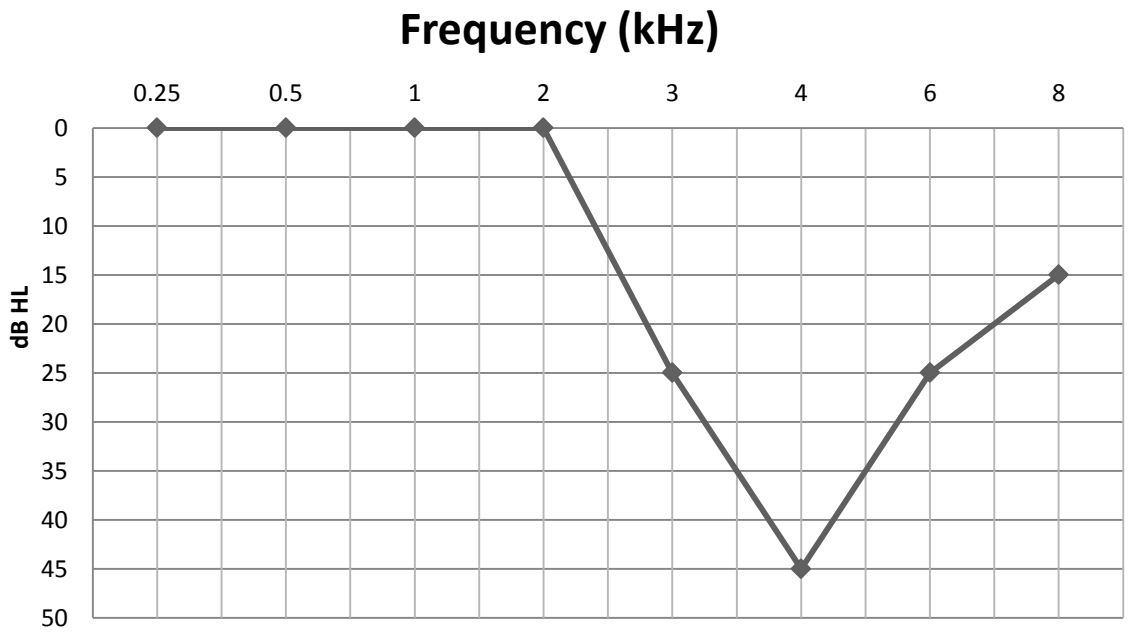



**Figure 2-9: Audiogram demonstrating the typical notch of NIHL. Source: Rabinowitz et al. (2006)**

Large studies involving thousands of workers with different exposure levels and durations were reviewed by ISO 1990:1999, ANSI (1996) and the U.S. Occupational Safety and Health Administration (US Department of Labor, 1983) based in part on the intergroup comparisons and analyses of Johnson (1978) (see chapter three for detailed consideration of these documents). All these groups published very similar tables of noise-induced permanent threshold shifts (NIPTS) based on the published data. Representative NIPTS values from the ISO 1990:1999 document are shown in figure 9.

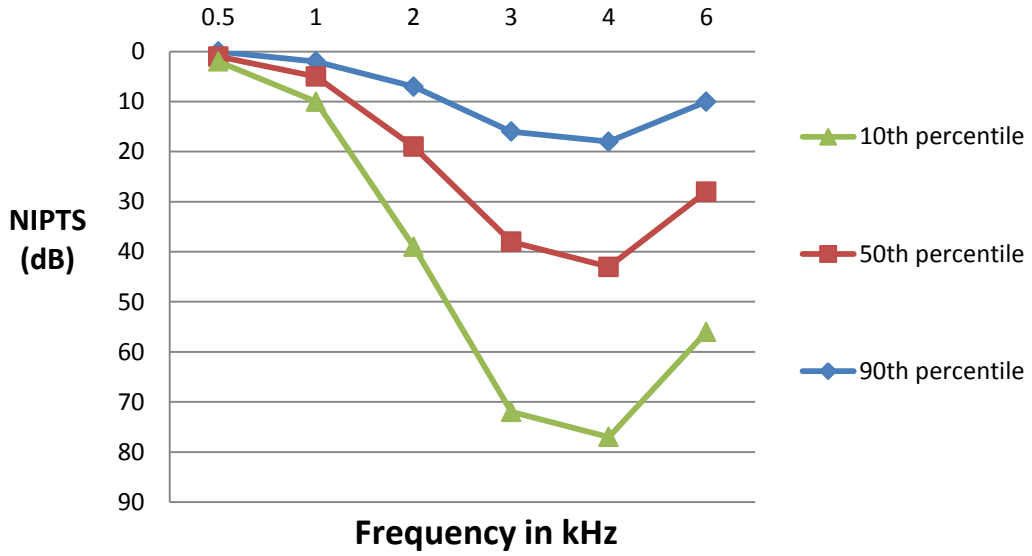



**Figure 2-10: Median (50th percentile) and extreme (10th and 90th percentiles) NIPTS after 30 years of workplace exposure to 95 dB A. Source: ISO 1990:1999**

The curves shown in figure 9 show plots of NIPTS values derived at by subtracting thresholds of control subjects from those of noise-exposed subjects[9]. A limitation of the ISO 1990:1999 and ANSI standards is that 8 kHz thresholds are not shown due to the lack of data from the underlying studies (ANSI, 1996; ISO 1990:1999). 8 kHz was shown to be an important frequency when clinical judgements are made about the typical notch observed in NIHL audiograms. Two recent, independent studies investigated the typical notch[10] observed in NIHL audiograms as a clinical tool to

[9] Extensive field studies of NIHL, all performed before widespread regulation of occupational noise exposure, were combined with studies of age-related hearing loss by the International Organization for Standardization (ISO, 1990) into ISO 1999 (Dobie, 2008).
[10] A noise notch requires better hearing at both lower frequencies and at 8 kHz than at the notch frequencies (American College of Occupational and Environmental Medicine (ACOEM), 2003).

judge NIHL audiograms (Rabinowitz, et al 2006; McBride & Williams, 2001). Rabinowitz and colleagues compared clinical judgement of the notch to those of notch metrics. These objective notch metrics that relied on the amount of recovery at 8 kHz were used as an indicator of the depth of the notch. It was concluded that clinical judgments about the 4 kHz notch were consistent and compared well to objective notch metrics, but both investigators found that audiogram reviewers differed in their valuation of notch depth[11] (McBride & Williams, 2001; Rabinowitz, et al 2006). The objective criteria used by Rabinowitz and colleagues are those of Coles et al. (2000) and Niskar et al. (2001). When investigating the prevalence of a notched audiogram or in clinical judgements of NIHL the definition of the notch is critical (Wilson, 2011). Available metrics providing notch criteria are summarised in table 2.2.

**Table 2-3 Notch criteria from Coles et al. (2000) and Niskar et al. (2001). Source: Rabinowitz et al. (2006)**

| | Application of the metrics | Notch criteria | Notes |
|---|---|---|---|
| Coles, Lutman, & Buffin (2000) | Published criteria for identification of an audiometric notch for use in medico-legal diagnosis of NIHL. | A high-frequency notch with the hearing threshold at 3, 4 and/or 6 kHz at least 10 dB greater than at 1 or 2 kHz and at least 10 dB greater than at 6 or 8 kHz | Because of distortion at 6 kHz, an adjustment would be necessary if certain earphone types were used. |
| Niskar, Kieszak, Holmes, Esteban, Rubin, & Brody (2001) | For use in identifying NIHL in the audiograms of adolescents tested in the National Health and Nutrition Evaluation Survey. | • Hearing-threshold level values at 0.5 and 1 kHz ≤15 dB;<br>• Worst (i.e., greatest value) threshold at 3, 4 or 6 kHz at least 15 dB worse than the worst threshold value at either 0.5 or 1 kHz<br>• A hearing threshold at 8 kHz at least 10 dB better than the worst threshold at 3, 4 or 6 kHz | |

A number of researchers have studied the occurrence of the noise-induced notch at frequencies other than 4 kHz (McBride & Williams, 2001; Sataloff & Sataloff, 2006; Osei-Lah & Yeoh, 2010; Axelsson, 1979; Salmivalli, 1979). More than three decades

[11] Notch depth is different to bulge depth (BD) as BD is used to define audiogram configuration. A simple BD statistic can be defined as the difference between the PTAs at 2, 3 and 4 kHz and at 1 and 6 kHz (Dobie, 2005).

ago researchers observed the notch at 6 kHz and concluded that the earliest change in hearing due to excessive noise exposure might be found at this frequency (Axelsson, 1979; Salmivalli, 1979). In a recent survey of the non-institutionalised population of the United States, the National Health and Nutrition Examination Survey (NHANES), data was collected from 2 819 women and 2 525 men between 1999 and 2004 (Ciletti & Flamme, 2008; Hoffman, Dobie, Ko, Themann, & Murphy 2010). Results from this survey revealed a small notch at 6 kHz for both men and women at younger ages (25 to 34 and 35 to 44 years). This notch was observed at the lower and upper percentiles. The observed 6 kHz notch in the NHANES data was attributed to an error in the reference value for audiometric zero when calibrating TDH-39 headphones on an NBS-9A (6 cm3) acoustic coupler (Hoffman, et al., 2010; Lawton, 2005). Another study by Lutman and Davis evaluated the hearing of young adults in the United Kingdom during a large random survey (Lutman & Davis, 1994). The researchers also raised concerns about the 6 kHz calibration bias after having found that the younger subjects (screened and unscreened) had unusually increased thresholds at this frequency. Rabinowitz and colleagues further warned that because of distortion at 6 kHz, an adjustment would be necessary if certain earphone types were used (Rabinowitz, et al., 2006).

Another explanation for the notch at 6 kHz provided by McBride and Williams (2001) was that the standardisation of hearing can explain the notch at 6 kHz. Hearing sensitivity is not the same across the range of audiometric frequencies represented in the audiogram. The hearing level (HL) reference levels are designed for testing hearing (Dobie, 2001). On the audiogram 0 dB HL is defined as the average threshold (across the frequency range) of hearing of normal hearing young adult subjects free of otologic disease (ANSI, 1996). The normalised shape of the audiogram should thus be a straight line, yet Robinson proposed that the reference standard at 6 kHz is set several dB too low with the result that a normal audiogram would have a notch at that frequency (Robinson, 1988).

The 4-6 kHz notch has also been attributed to other causes such as viral infections, skull trauma, hereditary hearing loss, ototoxicity, acoustic trauma, sudden hearing loss and multiple sclerosis (Martini, Stephens, & Read, 2007; Sataloff & Sataloff, 2006; Osei-Lah & Yeoh, 2010). In a recent study of 149 outpatients it was found that 62 (41,6%) had notched audiograms with only three of these participants reporting

histories of noise exposure (Osei-Lah & Yeoh, 2010). These results show that 4 kHz notches appear in audiograms of individuals with no significant exposure to noise. On the contrary 4 kHz notches can be absent in audiograms of individuals with extensive exposure to noise as shown by a recent study by Wilson (2011). This large study investigated the notches found in the audiograms of 3 430 veterans (Wilson, 2011). A notched audiogram (4 kHz) was observed in 40,6% of the participants with unilateral notches almost twice as prevalent as bilateral 4 kHz notches. These authors conclude that 4 kHz notches appear to be a random occurance in that most notches are unilateral with an equal likelyhood of occurance in the left and right ear. In conclusion the 4 kHz or any other high frequency notch without evidence of excessive noise exposure should not be deemed diagnostic of NIHL (Osei-Lah & Yeoh, 2010; Wilson, 2011) and conversely hearing loss with evidence of exposure to hazardous noise should not be disregarded as NIHL because of the absence of a high frequency notch.

## 2.6. Individual susceptibility and confounding factors in NIHL

According to the ISO 1990:1999 database, an exposure of 100 dB A for an 8 hour workday for 30 years (without the use of hearing protection) gives a median NIHL at 4 kHz of 45dB but with a range of 60dB between the 10th and 90th percentiles. From this example it is apparent that a noise-exposed individual may have normal hearing or severe hearing loss with the same noise exposure level and exposure time. Humans demonstrate differences in susceptibility to noise damage even under carefully controlled exposure conditions (Henderson & Hamernik, 1995).

Several factors play a role in individual susceptibility (vulnerability) to NIHL. These factors range from accompanying environmental factors such as non-occupational noise exposure and vibration, and biological factors such as smoking, age, gender, genetics, ototoxic drugs and illnesses such as tuberculosis (Pyykkö, Toppila, Zou, & Kentala, 2007). Some of these agents may accompany hazardous noise in or away from the workplace. The resultant hearing loss is often greater than would be expected for either agent alone (Dobie, 2001). Yet it is important to note that these agents cannot lower the levels and durations of noise at which the hazard begins (Kryter, 1965; Dobie, 2001; Martini, Stephens, & Read, 2007).

Although there are many factors contributing to individual susceptibility to NIHL the factors most relevant to this study are discussed in the following sections. The interaction of age and NIHL will be highlighted, with reference to the effect of smoking and genetics on susceptibility to NIHL. Finally the effect of gender and ethnicity on NIHL will be considered.

### 2.6.1. Age

A contentious issue when estimating the effect of noise on hearing relates to the effect of aging on hearing loss. Because of the many similarities and interactions between NIHL and age-related hearing loss (ARHL) many authors believe that it is imperative to take into account the contribution of ARHL when determining the effect of noise on hearing (Ciletti & Flamme, 2008; Niskar, Kieszak, Holmes, Esteban, Rubin, & Brody, 2001; Pyykkö, et al., 2007; Dobie, 2001; Hoffman, et al., 2010; Flamme, Deiters, & Needham, 2011). In a study by Dobie (2008) predictions were made about the burden of NIHL and ARHL in the United States (US). This author estimated that 10,5% of all hearing loss cases in the US can be attributed to NIHL. Although Dobie (2008) uses a different methodology than the large WHO study (Nelson, et al., 2005a) and criticises some aspects of the methodology of a large WHO study their estimates of the contribution of NIHL is similar (WHO study, 9%). Dobie (2008) arrives at the conclusion that most, estimated to be as high as 80%, of the burden of adult-onset hearing impairment is age-related.

Several similarities between ARHL and NIHL make it difficult to distinguish the relative contribution of aging and noise to hearing loss (Dobie, 2008). Firstly ARHL and NIHL show similar pure tone patterns on the audiogram (sensorineural, bilateral, with high frequencies affected more than low frequencies). Secondly, as described in the previous section, the audiogram of a person affected by NIHL typically demonstrates a notch in the 3 to 6 kHz region but this notch may be obliterated by age-related threshold shifts, as the worst affected threshold in ARHL is often at 8 kHz. Finally other tests (audiometric, oto-acoustic emissions, imaging etc.) do not reliably distinguish ARHL from NIHL (Dobie, 2008). Studies have shown that the effect of noise on hearing is most in the early years of exposure to hazardous noise levels but in later years (older than 65) the age-related hearing loss contributes more

to the total loss of hearing than NIHL (Dobie, 2008; Pyykkö, Toppila, Howard, Jacobs, & Kentala, 2007b). Researchers experimenting with mice confirmed these findings when they reported that animals showed less of a change in hearing when they had been exposed to hazardous noise and already had a large PTS, compared to animals with little or no previous NIHL (Perez, Freeman, & Sohmer, 2004). These authors suggest that hearing loss lowers the intensity of subsequent noise exposures and make the cochlea less sensitive. It is thus possible that initial NIHL affects subsequent NIHL as the noise levels are in effect lowered. ARHL could have the same "protective" effect as NIHL.

The mechanism of progressive pathological changes and damage to the cochlea caused by aging (and resulting in hearing loss) could be related to nutritional, vascular, toxic, genetic and other factors (Alberti, 2001; Bohne, Harding, & Lee, 2006; Clark, 2000; Dobie, 2008; Harding, et al., 2005; Martini, Stephens, & Read, 2007; Ferrite & Santana, 2005; Fransen et al., 2008). Very often these same factors have been indicated to increase a person's susceptibility to NIHL.

#### 2.6.1.1. Age, smoking and NIHL

In a study done by Ferrite and Santana (2005), the joint effects of *smoking*, age and occupational noise exposure were investigated in a cross-sectional cohort of 535 male workers. For smoking and noise exposure the estimated sum of the hearing loss was higher than the effects from each isolated variable in the 20 to 40 year age group. Increased susceptibility demonstrated in this study was confirmed by numerous other studies (Agrawal, Platz, & Niparko, 2009; Pouryaghoub, Mehrdad, & Mohammadi, 2007; Wild, Brewster, & Banerjee, 2005). In the Ferrite and Santana report (2005) the higher estimated hearing loss associated with a combination of smoking and age among the group who had not been exposed to occupational noise was also evident. The synergistic effect of smoking, noise exposure, and age on hearing loss, found in this study, is consistent with the biological interaction. These authors suggest that the synergistic effect of smoking, noise exposure, and age on hearing loss can be explained by the underlying mechanisms of damage relating to vascular changes and consequent cochlear hypoxia. In South Africa's population of mine workers the habit of smoking is very evident as confirmed by a study

investigating the prevalence of smoking in a group of platinum mine workers (n=25 274) (Cheyip, Nelson, Ross, & Murray, 2007). Although a decrease in cigarette consumption has been reported since legislation became more stringent (1990s) the prevalence of smoking has been reported to be about 43% of all platinum miners.

#### 2.6.1.2. Age, genes and NIHL

Recently observed pathophysiological changes to the cochlea, due to gene mutations, have led to more research in genetic hearing loss (Martini, Stephens, & Read, 2007). There is increasing evidence that genetic mutations could determine an individual and intrinsic predisposition to noise damage (Le Prell, et al., 2007; Harding, et al., 2005; Martini, Stephens, & Read, 2007; Konings, et al., 2009; Bovo, Ciorba, & Martini, 2007). Many of the contributions to the study of genetic factors in NIHL derive from laboratory research on genetically modified animals. Bovo and colleagues (2007) refer to three gene loci contributing to NIHL susceptibility that have been identified in strains of mice, 10 that contribute to ARHL, and six loci that promote both (Bovo, Ciorba, & Martini, 2007). The investigators concur that any gene that weakens the ear functionally or structurally would make it more susceptible to noise damage. Harding, Bohne and Vos (2005) further investigated the relationship between NIHL and an age-related gene found in mice. Their results confirmed that mice with the age-related gene (*Ahl)* were more susceptible to NIHL than those without.

#### 2.6.1.3. Age correction and the NIHL audiogram

Because of the interaction and co-existence of ARHL and NIHL age correction by use of available databases could be used to establish the contribution of NIHL to the total hearing loss (Dobie, 2001). It is argued that the individual's total hearing loss should almost always be treated as the sum of at least two components, NIPTS and age-related permanent threshold shift (ARPTS). If HTL refers to the hearing threshold level for a given frequency or pure-tone average: HTL= NIPTS+ARPTS (Dobie, 1992). Extensive field studies of NIHL, all performed before widespread regulation of occupational noise exposure, were combined with studies of ARHL by

the International Organization for Standardization (ISO, 1990) into ISO 1990:1999, a standard that describes the separate and combined effects of aging and noise on hearing thresholds in populations of varying age, sex, and noise exposure history (ISO, 1990). Data used in the ISO 1990:1999 was derived from a technical report prepared by Johnson (1978). These distributions were derived from the first National Health Examination Survey (NHES I, 1959–1962). It has subsequently been suggested that the National Health and Nutrition Examination Survey 1999–2004 distributions could be used as a possible replacement for Annex B (unscreened database) in ISO 1990:1999 (Hoffman, Dobie, Ko, Themann, & Murphy, 2010). The ISO 1990:1999 is widely used to estimate the contribution of age and noise to the individual or group's hearing threshold levels (Ciletti & Flamme, 2008; Hoffman, et al., 2010; Dobie, 2005; Dobie, 2008; Dobie, 2007; Flamme, et al., 2011; Pyykkö, et al., 2007).

Even though this data-base is viewed as the best available summary of the permanent effects of noise exposure on hearing thresholds investigators are warned about important pitfalls when using population standards for comparison (Dobie, 2008). Pitfalls include non-random selection of study groups as this could introduce biases that will make comparison to a standard invalid (Dobie, 2006). When using the ISO 1990:1999 the choice of which annex to use for comparison is very important. This International Standard allows for two possibilities presented by two different databases: Annex A represents an "otologically normal population ("highly screened")" (ISO, 1990, p. 1). It further assumes median thresholds of 0 dB HL at age 18 years. This assumption has been countered by population data from the United States NHANES (1999-2004) that showed thresholds between 0 and 7 dB HL for this age group (Flamme, et al., 2011). Annex B includes results from subjects "for an unscreened population (ISO, 1990, p. 1). This database includes some people with unreported occupational noise exposure, but is more representative of the general population (Dobie, 2008). For an unscreened group Annex B would be the most suitable comparison group. When making comparisons to the ISO standard or any other population standard it is important to note which thresholds are used for comparison. For Annex A thresholds of either ear could be used, where "better ear" thresholds are used in Annex B (ISO 1990:1999). It is not specified however, how these thresholds were derived at. It is possible that the better ear was derived at by

using pure tone average (PTA) (Dobie, 2006) or it is likely that the ear contributing to the better ear distribution could vary with frequency, depending on which ear have the better thresholds at that frequency (Flamme, et al., 2011). The latter assumption has been proven by analysis of the raw data tapes (Hoffman, Dobie, Ko, Themann, & Murphy, 2010).

Finally, when making comparisons it is important to choose the appropriate methods of statistical analysis. Because Annex A and B show positively skewed distributions (where means (averages) are greater than medians (the mid-point) and to a larger extent spread above the median than below it), median values and other percentiles were used to describe the data. Similar descriptors should be used when comparing data to the ISO databases (Dobie, 2006).

### 2.6.2. Gender

A recent study by Flamme, Deiters and Needham (2011) investigated cumulative pure tone threshold distributions from the National Health and Nutrition Examination Survey (NHANES) III and the 1999–2004 data (which can be generalised in respect of a population without significant history of exposure to occupational noise) by gender, ethnicity, age, ear, and the stimulus frequency. They found that pure tone hearing thresholds were worse for men than for women, and although the differences became more pronounced with increasing age and at higher frequencies, the differences were present across the age span and in each race/ethnicity category (Flamme, et al., 2011).

Adolescent and young adult males have been shown to have worse hearing thresholds than females (Le Prell, Hensley, Campbell, Hall III, & Guire, 2011) and these gender-based differences extend into adulthood, as the results of a study by Ciletti and Flamme (2008) with a large cohort of males (N=3275) and females (N=3711) demonstrate. These researchers used data from NHANES 1999-2004 and a large cohort of rural subjects (Keokuk County Rural Health Study (KCRHS)). Results indicated that rates of hearing impairment among men were twice as high as among women.

Even in the absence of occupational noise exposure men show significantly poorer threshold results than women. These results may be explained to some extent by women being less exposed to leisure noise (Pyykkö, et al., 2007). The study done by Le Prell and colleagues (Le Prell, Hensley, Campbell, Hall III, & Guire, 2011), notwithstanding the limited sample size (N=56), showed a statistically reliable relationship between personal music player use and lower thresholds in female subjects. They provide greater noise/sound exposures in males than in females as a possible explanation for greater hearing loss in males than in females, but the results might also indicate greater susceptibility to NIHL in males than in females.

As the other large studies based on the NHANES data (Flamme, et al., 2011; Ciletti & Flamme, 2008) have not controlled for non-occupational noise exposure as a variable, it is also possible that the argument for susceptibility for hearing loss may be reversed. Non-occupational noise exposure might not play a significant role and women might be less susceptible to hearing loss in general. The latter statement is confirmed by different correction factors in international and other standards for females and males that indicate better hearing thresholds (overall) in females across different age groups (ANSI, 1996; ISO 1990:1999). Several studies confirm better hearing in general in females (Henselman, Henderson, Shadoan, Subramaniam, Saunders, & Ohlin, 1995; Flamme, et al., 2011; Ciletti & Flamme, 2008; Dreisbach, et al., 2007, Agrawal, et al., 2010; Nelson, et al., 2005a). In a study on the effects of gender on hearing thresholds a significant gender effect was also found at the ultrahigh frequencies (14000-16000 kHz) with better thresholds for female subjects (Dreisbach, et al.,, 2007).

Many other authors have found a significant and relatively large difference in vulnerability or susceptibility for NIHL between men and women (Berger, Royster, & Thomas, 1978; ISO, 1990; Smith, Davis, Ferguson, & Lutman, 2000; Rabinowitz, et al 2002). In a comprehensive study by the WHO a comparative risk assessment was done incorporating the results from 16 studies and 14 WHO epidemiological subregions (Nelson, et al., 2005a). Results from this study demonstrated that the effects of the exposure to occupational noise are larger for males than females in all subregions and higher in the developing regions. NIHL reportedly affects males at a 3:1 higher rate than females (Nelson, et al., 2005a) indicating greater susceptibility to NIHL.

### 2.6.3. Race

The hearing threshold levels of occupational noise-exposed individuals have also been compared between subjects of different ethnicities (Rabinowitz, et al 2002; Ishii & Talbott, 1998). In an extensive study investigating hearing thresholds of a large group of US army soldiers (N=39006) a significant difference was found between black and white soldiers' hearing thresholds after correcting for age and noise exposure (Henselman, et al., 1995). Black soldiers had better hearing than white soldiers across the frequency range. The study of Rabinowitz and colleagues (2002) showed similar results, despite small numbers of racial sub groups: black subjects showed a trend toward better audiometric thresholds and oto-acoustic emissions (OAE).

In a study by Ishii and colleagues (1998) black metal fabricating workers had a PTA (1, 2, 3, 4 kHz) of 17,71 dB compared to their white counterparts who showed a PTA average of 25,99 dB, a statistically meaningful difference ($p < 0.01$). Several reports on the effect of eye colour in susceptibility to NIHL (Carter, 1980; Ishii & Talbott, 1998; Carlin & McCroskey, 1980; Cunningham & Norris, 1982) indicate that individuals with blue eyes are more susceptible to noise-induced cochlear damage than are green or brown-eyed individuals which may be related to race since eye colour is highly dependant on race. This clinical research suggests that melanin,[12] especially in the stria vasclaris of the cochlea, appears to act as a protective agent (Ishii & Talbott, 1998). In accordance with these results researchers Pyykkö, Toppila, Zou, and Kentala (2007) found that skin sensitivity to sunburn (pigmentation) seems to affect vulnerability to NIHL. This has also been attributed to higher levels of melanocytes and their protective capability against noise damage in the inner ear. These results and conclusion might explain why black subjects have presented with significantly better hearing thresholds compared to white subjects and less susceptibility to NIHL than the latter.

In South Africa a very large porportion of the mining workforce is black (referred to as African) compared to a much smaller white group. Anglogold Ashanti, the

[12] Melanin is the the dark amorphous pigment that covers the posterior surface of the eye which appears in skin and exists in differing amounts in eyes and skin. Blue eyes are at one end of the continuum and are almost entirely lacking in melanin, whereas dark brown eyes are at the other extreme and have a relatively greater amount of melanin (as with darker skin colour) (Carlin & McCroskey, 1980).

goldmine whose workers were investigated in this study, for example permanently employed 19 897 black mine workers compared to 3 820 white workers in 2010 (excluding infrastructure support workers) according to their employment equity report (AngloGoldAshanti, 2010). To date only one large scale study has been done investigating NIHL in South African mine workers. This study investigated NIHL in a cohort of white South African male mine workers (N=2667) (Hessel & Sluis-Cremer, 1987). As no black or female workers were included in this cohort, comparisons between these groups and respective susceptibility to NIHL are unavailable.

## 2.7. Summary

In this chapter, a historical overview was provided for NIHL. The discussion has shown that NIHL was described very early on in history and is still very prevalent today. In South Africa, as elsewhere on the globe, NIHL is also prevalent and has been identified as a major occupational hazard in mining in South Africa. The mechanism of NIHL and the nature of the structural and other changes in the cochlea have been discussed and new research endeavours have been highlighted. The literature overview has provided insight into the effect of NIHL on the audiogram and controversies in the field, specifically related to the “noise notch”, have been considered. Finally different confounders that might affect outcomes of hearing threshold results of this study were discussed. It is clear from literature that age plays a very important role in hearing and NIHL cannot be investigated without taking the effect of aging into account. Other important risk factors, such as smoking, ethnicity (race) and gender influence susceptibility to NIHL and affect hearing thresholds. Available published reports suggest that black subjects tend to have better hearing thresholds overall as do female subjects.