Original articles

The impact of diving on hearing: a 10–25 year audit of New Zealand professional divers

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Key words
Audiology; Fitness to dive; Hearing loss; Medicals – diving; Occupational diving; Surveillance

Abstract
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Introduction: Surveillance of professional divers' hearing is routinely undertaken on an annual basis despite lack of evidence of benefit to the diver. The aim of this study was to determine the magnitude and significance of changes in auditory function over a 10–25 year period of occupational diving with the intention of informing future health surveillance policy for professional divers.
Methods: All divers with adequate audiological records spanning at least 10 years were identified from the New Zealand occupational diver database. Changes in auditory function over time were compared with internationally accepted normative values. Any significant changes were tested for correlation with diving exposure, smoking history and body mass index.
Results: The audiological records of 227 professional divers were analysed for periods ranging from 10 to 25 years. Initial hearing was poorer than population norms, and deterioration over the observation period was less than that predicted by normative data. Changes in hearing were not related to diving exposure, or smoking history.
Conclusion: Audiological changes over 10 to 25 years of occupational diving were not found to be significantly different from age-related changes. Routine annual audiological testing of professional divers does not appear to be justifiable.

Introduction

Hearing loss is recognised as an important and preventable occupational injury. In most industries, exposure to excessive noise is the responsible mechanism, and where all other measures to reduce noise levels have been exhausted, employers are obligated to provide hearing protection and appropriate staff education. For working divers, however, hearing can be adversely affected by several mechanisms that are independent of noise exposure. These include: conductive loss due to middle ear barotrauma (MEBt), which impairs transduction of sound by the tympanic membrane and ossicular chain;[1] sensorineural deficit due to noise-induced hearing loss (NIHL); barotraumatic damage to the inner-ear structures[2,3] and inner ear decompression sickness (DCS).[4,5] Apart from these discrete barotraumatic and DCS events, doubt remains as to whether diving *per se* has a clinically significant negative impact on hearing over the long term. Controlling for the effects of increasing age and discrete injurious events remains a confounding factor for research in this area. The value of such research, for divers and employers, is that after identifying and either eliminating or minimising any preventable causes of hearing loss, including high-risk diving practices, they could have realistic, evidence-based, expectations about the impact of diving on hearing. The objective of the current study was to identify evidence of hearing loss that appears related to long-term occupational diving, with the intention of informing auditory surveillance policy for divers.

Reviews of diving-related hearing loss suggest that long-term changes are not clinically significant, and that, after correcting for age, any deterioration is likely due to noise exposure or trauma.[6,7] However, results of individual studies are variable, with some studies reporting significant hearing loss and a correlation with diving experience, and others reporting no such loss or correlation. For example, it was found that at most frequencies, divers had poorer hearing than age-matched otologically normal subjects at both the initial and final examination six years later.[8,9] Also, a significant correlation was found between hearing loss and both diving experience and smoking. Similarly, in a

Table 1
Characteristics of 227 occupational divers undergoing audiological testing over periods of between 10 and 25 years; *n* – number (mean or median); * – 2nd medical refers to data collected from each diver's most recent medical examination; number of dives refers to the year prior to the most recent audiometry

Characteristic	*n (% or range)*
Male	204 (90)
Female	23 (10)
Non-smoker	166 (73)
Smoker and ex-smoker	61 (27)
Dives/year (at 2nd medical*)	39 (median) (0–350)
Age (at 2nd medical*)	47 (median) (31–75)
BMI (at 2nd medical*)	27.1 ($kg \cdot m^{-2}$) (18.8–40.8)
Age change (yrs)	12 (median) (10–25)
Scientific	80 (35)
Commercial	45 (20)
Instructor	37 (17)
Construction	33 (14)
Aquaculture	15 (7)
Military/Police/Customs	8 (3)
Film	8 (3)
HBU attendant	1 (< 1)

prospective series of studies of professional divers over a twelve year period, although divers had better hearing than the general population at both initial and final examinations (in contrast to the above findings), minor reduction in hearing seemed related to diving exposure.[10–12] Similar results were reported in a five-year prospective study of Japanese fishery divers,[13] and in a cross-sectional study of Malaysian Navy divers whose hearing deteriorated at a faster rate than controls.[14] However, in a previous cross-sectional study, no differences were found between the hearing of a group of construction divers with a mean of 20 years' diving experience and a matched control group of workshop workers.[15] Another prospective study of professional divers over six years reported no correlation between hearing loss and diving frequency or history of middle ear barotrauma.[16] Other studies of professional divers have also found no significant difference in hearing between divers and control subjects or a relationship between hearing loss and diving experience.[17–19] Most studies of recreational divers have reported no significant hearing impairment compared with control subjects.[20–24] All this suggests that increased noise exposure, more likely to be encountered by professional divers, is the most plausible explanation for any finding of increased hearing loss in that group. A comparison of professional divers and offshore workers found that these divers were indeed more likely to suffer noise-induced hearing loss.[25]

As one of only two mandatory physical investigations routinely required of professional divers, the other being assessment of lung function, investigation of the evidence underlying the requirement for audiometry, repeated annually in most countries, is both apposite and overdue.

Method

This study was reviewed and authorised by the Waitemata District Health Board Research and Knowledge Centre and was deemed not to require full review by a Health and Disability Ethics Committee (reference no. RM13630). As part of their medical assessments, all divers signed consent for the use of their anonymised health data for research purposes.

The New Zealand occupational divers' database was audited for all divers with two hearing assessments separated by at least 10 years. We used the earliest hearing assessment available on our database as their baseline, but this was not invariably the first hearing assessment in the diver's career. To clarify, the duration of occupational diving between assessments was not necessarily equivalent to the total occupational diving experience of any diver. Qualifying divers' records were also audited for a history of middle (MEBt) or inner (IEBt) ear barotrauma, inner ear DCS, pre-existing hearing loss or tinnitus.

Initial and follow-up recordings of pure tone air conduction hearing thresholds, in decibels (dB), were collated for each ear for the frequencies of 500 Hz, 1, 2, 4, 6 and 8 kHz. For each of these recordings, a corresponding age-adjusted value was calculated by subtracting from the observed value, the median normal hearing threshold, derived from the appropriate ISO 7029:2017 prediction equation for otologically normal subjects, based on age and gender.[26] This model uses, as the reference zero level, the median of the 18-year old population. So, for example, the recorded thresholds for an 18-year old would require no adjustment. The changes in both recorded and adjusted values were calculated between the initial dataset and the paired dataset recorded after a period of 10–25 years of occupational diving. Correlations were sought between changes in hearing and duration of professional diving experience, intensity of

Figure 1

Age-adjusted, initial observed and predicted hearing thresholds of 227 divers (medians and 95% confidence limits); predicted values were derived from ISO Standard 7029[26]

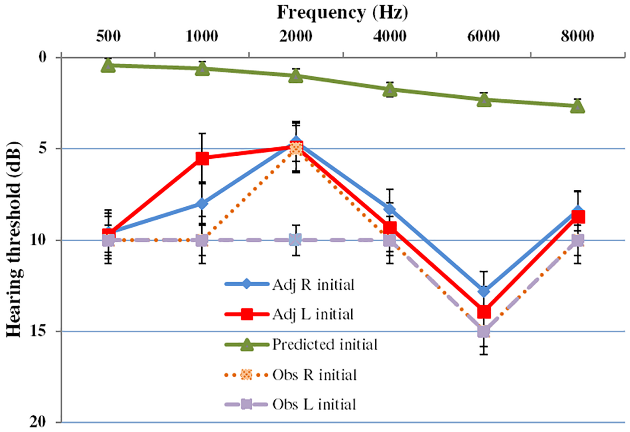


Figure 2

Age-adjusted, observed and predicted hearing thresholds of 227 divers after 10–25 years of diving (median and 95% confidence limits); predicted values were derived from ISO Standard 7029[26]

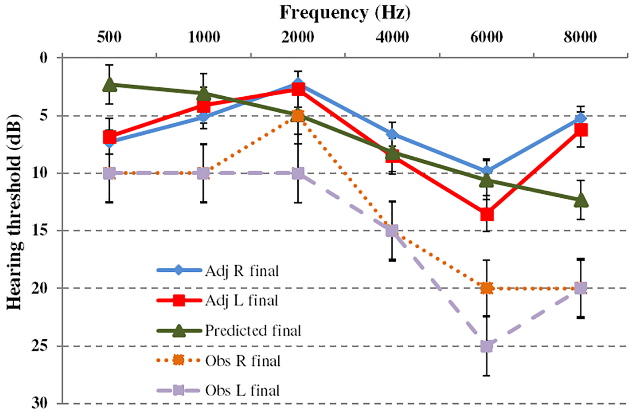


Figure 3

Degree of hearing loss at certain frequencies in 227 divers over 10–25 years

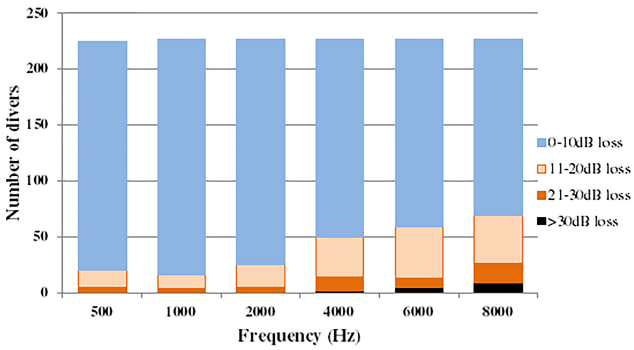
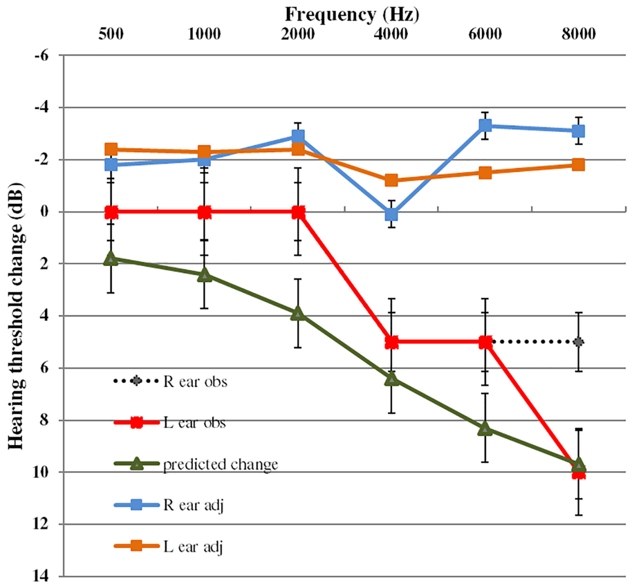


Figure 4

Change in observed and age-adjusted hearing thresholds over 10–25 years of diving compared with predicted change (medians and 95% confidence limits); predicted values were derived from ISO Standard 7029[26]



diving (as described below), smoking status (categorised as non-smokers, ex-smokers and current smokers) and body mass index (BMI).

Statistical analysis used SAS® v9.4 software (SAS Institute Inc., Cary, North Carolina, USA). Frequency and proportion (%) were used for describing categorical variables, such as gender, smoking status and type of diving. Median with minimum and maximum were used for describing the continuous variables including age (and change in age used to represent duration of diving experience), BMI and number of dives per year, as they did not follow a normal distribution. Median, and its distribution-free 95% confidence intervals, were used to present the study outcomes including observed, predicted and age/gender-adjusted values of hearing thresholds. Robust regression models (using the ROBUSTREG procedure, an alternative to least squares regression, that provides stable results in the presence of outliers, and limits their influence) and analysis of co-variance with general linear models were used in multiple regression analyses. A P-value of < 0.05 was considered to be statistically significant. Type 1 error was not adjusted for multiple comparisons, in order to allow for outliers and include all possible important information.

Results

Two-hundred and twenty-seven divers satisfied the entry criterion of having adequate records spanning periods of 10–25 years (median 12 years). Demographic data for the divers are presented in Table 1.

None of the divers had a recorded history of either IEBt or DCS, but two had a history of MEBt, and 44 (19.4%) had a record of either pre-existing hearing loss and/or chronic

Table 2

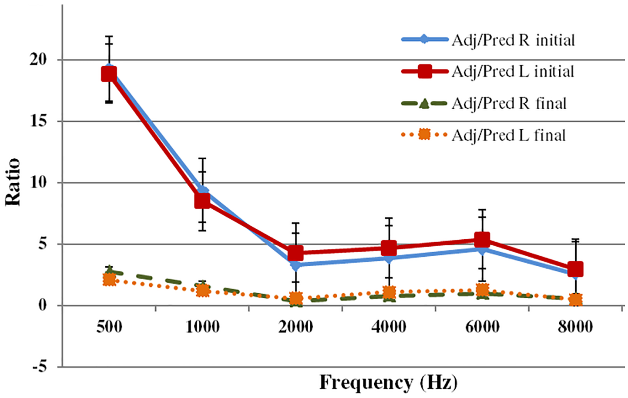
Changes of the observed, age-gender-adjusted and predicted hearing threshold values of 227 occupational divers over 10–25 years of diving; * 25 percentile; ** 75 percentile; *** predicted values were derived from ISO Standard 7029[26]; all values are expressed in decibels (dB)

Frequency (Hz)	Side	Median	95% CI of median		Q1*	Q3**	Interquartile range
			Lower	Upper			
Change in observed values							
500	R	0	0	0	-5	5	10
500	L	0	0	0	-5	5	10
1000	R	0	0	0	-5	5	10
1000	L	0	0	0	-5	5	10
2000	R	0	0	0	-5	5	10
2000	L	0	0	0	-5	5	10
4000	R	5	5	5	0	15	15
4000	L	5	5	5	0	15	15
6000	R	5	5	10	-5	15	20
6000	L	5	5	10	0	15	15
8000	R	5	5	10	0	15	15
8000	L	10	5	10	0	20	20
Change in age/gender- adjusted values							
500	R	-1.8	-2.8	-1.2	-7.9	3.6	11.5
500	L	-2.4	-3.8	-1.4	-7.7	3.3	11.0
1000	R	-2.0	-3.6	-1.2	-7.0	3.2	10.3
1000	L	-2.3	-3.4	-1.6	-7.4	2.5	9.9
2000	R	-2.9	-3.9	-2.0	-8.0	2.4	10.4
2000	L	-2.4	-3.7	-1.7	-7.8	2.0	9.8
4000	R	0.1	-1.9	1.1	-7.3	5.3	12.5
4000	L	-1.2	-2.9	0.9	-8.5	6.1	14.7
6000	R	-3.3	-4.6	-1.1	-10.5	6.1	16.7
6000	L	-1.5	-3.1	0.4	-8.9	5.8	14.7
8000	R	-3.1	-5.3	-0.8	-10.0	7.5	17.4
8000	L	-1.9	-3.5	0.4	-9.8	8.7	18.5
Change in predicted values*							
500	both	1.8	1.6	2.0	1.1	3.0	1.9
1000	both	2.4	2.1	2.6	1.4	3.9	2.5
2000	both	3.8	3.1	4.1	2.3	6.1	3.8
4000	both	6.3	5.5	6.7	3.8	9.6	5.8
6000	both	8.0	7.1	8.5	4.9	12.2	7.3
8000	both	9.4	8.2	10.0	5.7	14.4	8.7

tinnitus. Both initial and final hearing thresholds for the group were higher than normal values, meaning that sounds were detected at a higher sound intensity and indicating that hearing was slightly worse than predicted for age. However, changes over the recording period were smaller than predicted by the relevant ISO Standard.[26] Both age-adjusted and observed hearing thresholds for right and left ears were compared with predicted (normal) values for initial (Figure 1) and final recordings (Figure 2). The median values and 95% confidence limits of changes in observed and predicted thresholds are shown in Table 2, together with 25 and 75 percentiles and interquartile ranges. Despite

Figure 5

Ratio of age-adjusted and predicted* hearing thresholds of divers before and after 10–25 years of diving (medians and 95% confidence limits); * predicted values were derived from ISO Standard 7029[26]



more than half of the group showing a significant hearing reduction in at least one ear and at one frequency, more notable at the higher frequencies (Figure 3), median values for the group showed no change in the hearing thresholds at lower frequencies (500 Hz, 1 kHz, 2 kHz) in either ear, and only minor changes at the higher frequencies (4 kHz, 6 kHz, 8 kHz) that were less than predicted for increasing age (Figure 4).

The reduction, over time, in the difference between age-adjusted recordings and predicted thresholds is further demonstrated by comparison of the ratio of median age-adjusted observations and predicted thresholds at initial and subsequent testing after 10–25 years of occupational diving (Figure 5).

This reduction in difference (approaching the predicted values) of thresholds is significantly more pronounced at the low frequencies (500 Hz and 1000 Hz). Multiple regression analysis, using the models described above, found no significant correlation between hearing change and intensity of diving or smoking status, but at most frequencies there was a statistically significant association with BMI ($P < 0.05$ for multiple comparisons). No correlation was found between hearing change and duration of diving apart from at 4 kHz in the left ear ($P = 0.034$) and 8 kHz in the right ear ($P = 0.038$).

Discussion

Our data show that, for this sample of 227 professional divers, there was less deterioration in hearing after 10–25 years of professional diving than would be expected in the age-matched general population. However, we do not suggest that diving confers a degree of hearing protection, as most of the demonstrated changes are too small to be clinically relevant, and fall within the margin of error of many commonly used audiometers. Our finding of a correlation between hearing loss and BMI at most of the tested frequencies was unexpected and of unlikely clinical significance. Previous studies have shown an association between high BMI and increased risk of hearing loss in adolescents[27] and adult women,[28] but not in adult men.[29]

Valid reasons for testing divers' hearing include determination of fitness for work (i.e., communication issues), tracking of hearing loss with the aim of prevention of further damage, and documentation of existing damage for possible future compensation claims. But whether the results of such tests are usually acted upon, and/or have a role in the prevention of further deterioration of hearing is debatable. Abnormal results mean that damage is already done or may imply a pre-existing condition. They could certainly point to modifiable causes, but *post hoc* rationalisation is an unsound basis on which to mandate formal routine audiological examinations. For example, while abnormal results do not imply an unsafe environment, normal results do not imply an audiologically safe working environment, that should ideally be provided, regardless of test results, by adherence to all practicable safety measures.

Our results concur with the majority of previous studies and suggest that, while professional divers are always at increased risk of hearing damage due to a specific traumatic incident, they are at no greater risk of hearing loss than the general public in the absence of such an incident. Of particular note, in the past fifteen years, since the introduction in New Zealand of five-yearly rather than annual full medical evaluations, not a single diver has been found, on routine audiological testing, to have a hearing condition that has resulted in any restriction on their certification. Employers, and divers themselves, are responsible for minimising exposure to excessive noise and other potential causes of hearing damage, such as barotrauma and DCS.

Consequently, we believe that a reasonable approach to surveillance of divers' health in this regard would be to perform formal audiological testing on entry to the industry, as a screening test and baseline, followed by further testing only if clinically indicated (for example, after a barotraumatic or inner ear DCS event), and then final testing on exit from the industry.

LIMITATIONS

Firstly, we did not have an objective measure of actual diving exposure, and our first audiometric recordings did not invariably represent the beginning of that exposure. The number of years of occupational diving between assessments, although a blunt measure, was used as a surrogate for diving exposure. In addition, as mentioned above, the number of years of occupational diving used in this study is not necessarily representative of an individual diver's complete diving career, as many divers had already been diving for several years before the earliest of our usable audiological records. We have reported the change in hearing over periods of occupational diving ranging from 10 to 25 years. However, the initial recordings represent the divers' hearing at various points in their diving careers. So, we cannot exclude the possibility that our initial recordings may have been influenced by existing damage which could, in turn, influence later changes. Divers with an initial history of MEBt, hearing loss or tinnitus were not excluded from this study, because they were still considered to be fit to dive, and including them produced a more complete record of the real-world situation for working divers. For the multiple regression analysis, diver occupational groups were stratified into 'high intensity' and 'low intensity' groups on the basis that the high intensity group, consisting of construction, commercial, and military divers, was more likely to be exposed to deeper and more exertional diving with greater likelihood of noise pollution from in-helmet communications or equipment, than the low intensity group. Again, we acknowledge that this classification may be subject to inaccuracies.

Another limitation of this study is the possibility that a selection or attrition bias (healthy worker effect), based on divers leaving the industry because of hearing problems, might have influenced our findings. The only way to resolve this question would be to compare the audiograms of all divers on entry to, and exit from the industry, a topic for ongoing study. Preliminary results of a study into health reasons for diver attrition (pending[30]) demonstrate no evidence of hearing loss being a reason for quitting diving.

As with all such audits, data gathered over many years and from many sources are subject to the vagaries of variable equipment quality and the technical competence of operators. We were limited to using pure tone air conduction data when a more complete data set would have included bone conduction and speech discrimination data.

Finally, we used the latest ISO Standard data set as the normative data for comparison. An appropriate alternative may have been to use a matched group with similar occupational noise exposure to divers, such as firefighters, a consideration for future study.

Conclusions

Audiological changes over 10–25 years of professional diving were not found to be significantly different from the changes expected due to ageing. Development of policies for health and safety surveillance of occupational divers should be guided by the best available evidence of benefit when determining the frequency and type of screening examinations required. The results of this study suggest that routine annual audiological testing of occupational divers is not justifiable.

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Conflicts of interest

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