IV

Hearing loss in divers: a six-year prospective study

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Abstract

BACKGROUND: Occupational diving is associated with hearing loss, but the cause is disputed. Our aim was to follow a cohort of divers through the first six years of their career in order to look for evidence of permanent threshold shift associated with diving activity, occupational noise exposure or acute injuries.

METHODS: Hearing was measured by pure tone audiometry in 67 participants at a basic course for working divers. Hearing thresholds were adjusted for age (ISO7029). The subjects were examined and interviewed by an otologist. Additional medical and exposure data were recorded in questionnaires and personal logbooks. The procedure was repeated after 3 and 6 years.

RESULTS: None of the subjects suffered inner ear barotrauma or inner ear decompression sickness during follow-up. Middle ear barotrauma was common. The prevalence of subjective hearing difficulties increased during follow-up, and there was a significant threshold shift at 4 kHz (mean: 2.6 dB, 95% confidence interval: 0.9 – 4.3 dB). Both subjective and objective hearing loss was associated with occupational noise exposure, but not with diving frequency or with a history of middle ear barotrauma.

CONCLUSION: In the absence of manifest inner ear barotrauma or inner ear decompression sickness, noise seems to be the most important cause of long-term hearing loss in occupational divers. This study did not find evidence of long-term hearing loss caused by uneventful diving *per se*.

Keywords: Inner ear, occupational noise, barotrauma, decompression sickness, pure tone audiometry

Introduction

There is evidence from several cohort studies that occupational diving is associated with hearing loss [1-3], but the cause is disputed. The main problem in longitudinal studies is to control for the effect of aging and to determine whether the measured threshold shift is due to diving itself, to acute injuries or to noise. This is of practical importance, since noise and acute injuries to some extent can be prevented.

Results from cross-sectional studies diverge. Edmonds found that severe hearing loss was common in Australian abalone divers [4]. Others have found more moderate differences when comparing divers to controls [5-8]. Some studies, particularly of recreational divers, have not demonstrated any difference at all between divers and the general population [9-11]. A possible explanation for this discrepancy is that hearing loss is caused not by diving per se, but by other factors that vary between different subpopulations of divers.

The aim of this study was to measure permanent threshold shift in a group of divers during the first six years of their career, and to examine whether it was associated with diving activity, noise exposure or acute injuries.

Methods

The protocol was approved in advance by the Regional Committee for Medical Research Ethics, which enforces the Helsinki Declaration on medical research involving humans. Participation in the study was based on written informed consent.

A cohort of 67 men aged 28 ± 5 years (mean ± SD) was recruited among participants at a basic course for professional divers at the Norwegian State Diving School. The response rate was 84%. The divers were examined at school, and after three and six years. Data for the whole period were available for 53 of them.

Hearing was measured by pure tone audiometry (air and bone conduction) in the frequencies 0.5, 1, 2, 3, 4 and 6 kHz. Middle ear pathology was assessed by otomicroscopy, impedance tympanometry and measurement of air-bone gap. All divers were examined and interviewed by an otolaryngologist with experience in diving medicine and otoneurology.

A detailed medical and occupational history was obtained through questionnaires and interviews. The number of dives performed by each subject was acquired by comparing information from the questionnaires, interviews and personal log books. The questionnaire elicited more detailed information on seven known risk factors for noise-induced hearing loss in divers [12]: operating high pressure waterjets, pneumatic rock drills, hydraulic rock drills, hydraulic wrenches/hammers, working close to DP-vessel propellers/thrusters, seismic explosions or to other explosions (e.g. from oxy-arc burning). The divers were also questioned about their use of different types of diving gear, i.e. heavy helmets, light helmets, band masks or scuba gear. They were allowed to select more than one category.

The diagnosis of inner ear injury was clinical based on history and findings. The possibility of injury was considered if at follow-up a diver reported cochleovestibular symptoms in relation to a dive or if there were new cochleovestibular signs. Middle ear barotraumas ('ear squeeze') were reported by the divers themselves in the questionnaire.

The following disorders were excluded at the initial examination: Hypertension, diabetes, a history of meningitis or ear surgery (apart from myringotomy). Hereditary, ototoxic or mechanical hearing loss (air-bone gap > 10 dB) was also excluded. The questionnaire included an item on cerebral concussion in order to assess whether hearing loss was associated with a history of head trauma.

We used PASW Statistics 18.0 (SPSS Inc., Chicago) for data analysis. The *Statistical distribution of hearing thresholds as a function of age* (ISO 7029) in otologically normal subjects was used in order to calculate age-adjusted thresholds [13] according to the following formula: age-adjusted threshold = observed threshold (dB_{HL}) - expected threshold (ISO 7029). Threshold shift was calculated as age-adjusted threshold after six years minus age-adjusted threshold in diving school. The level of statistical significance was taken as $\alpha = 0.05$. Age-adjusted hearing thresholds were entered into a multivariate repeated measures ANOVA model in order to test whether hearing changed during follow-up. The multivariate analysis tested all six frequencies simultaneously. Then each frequency was analyzed individually by univariate analysis. Only frequencies with significant shift in the univariate ANOVA were analyzed further. The threshold shifts were approximately normally distributed. The effect of potential risk factors on hearing threshold shift was estimated using t-tests and linear regression. Cochran's test for equality of proportions in related samples was used in order to examine the frequency of subjective hearing problems during follow-up. The effect of potential risk factors on subjective hearing symptoms at follow-up was estimated using logistic regression.

Results

At follow-up the divers had been working inshore, mainly in fishery (scallops, sea farming), construction and salvage to a maximum depth of 50 m. The total and median number of dives during follow-up was 27,232 and 430 (interquartile range – IQR: 150 - 950) respectively. No divers were treated for decompression sickness (DCS), but at follow-up two reported having had symptoms that, in retrospect, could have represented DCS. One diver reported skin symptoms only, while the other reported transient neurological symptoms (visual disturbances and fatigue). No cases of inner ear DCS or inner ear barotrauma were diagnosed, but in the questionnaire 17 divers reported having experienced middle ear barotrauma (‘ear squeeze’).

Self-reported difficulty understanding speech in background noise was present in 2, 4 and 9 divers at the first, second and third examination respectively. The increase was significant ($p < 0.01$). The odds for reporting such difficulties at follow-up were mainly associated with age and occupational noise exposure (table 1).

Table 1 The effect of potential risk factors on subjective hearing loss[a] six years after completing a basic course for professional divers. Number of exposed subjects, unadjusted odds ratios and 95% confidence intervals. Odds ratios were estimated by logistic regression for exposed vs. non-exposed subjects or per unit of exposure.

	n	OR		95% CI	
Age (odds ratio per decade)		5.4	*	1.0	28
Noise exposure related to diving (divers confirming exposure to the following underwater noise sources)					
1. Waterjet	19	4.2		0.9	19
2. Pneumatic rock drill	35	1.5		0.3	8.3
3. Hydraulic rock drill	16	1.9		0.4	8.2
4. Hydraulic wrenches/hammers	19	4.0		0.9	19
5. Working close to DP-vessel propellers	3[b]				
6. Working close to seismic explosions	1[b]				
7. Exposure to other explosions (e.g. from oxy-arc burning)	6	2.5		0.4	16
Odds ratio per noise source (1-7)[c]		1.8	*	1.1	3.2
Noise exposure in general					
Have you ever experienced noise leading to tinnitus?	37	3.0		0.3	27
Use of firearms (military or civilian)?[d]	15	1.2		0.2	5.5
Diving equipment (more than one alternative could be selected)					
Standard heavy helmet	11	1.0		0.2	5.4
Light-weight helmet	26	1.9		0.4	8.7
Band mask	38	2.7		0.3	24
Scuba gear	38	1.0		0.2	5.8
Diving activity (odds ratio per 100 dives)		1.1		1.0	1.3
Family history of hearing loss[e]	14	3.1		0.7	14
History of otitis	16	2.3		0.5	11
History of cerebral concussion	23	2.7		0.6	12
History of middle ear barotrauma	17	1.7		0.4	7.4
Tobacco smoking (past or present)	17	0.9		0.2	4.1
Alcohol consumption (weekly or more often)	23	1.7		0.4	7.3
Binge drinking ("getting drunk" monthly or more often)	28	0.6		0.1	2.7

[a] Divers reporting increased difficulty understanding speech in background noise (n = 9)
[b] Odds ratio not calculated due to few positive answers
[c] Adding one noise source, regardless of type, increased the odds for subjective hearing loss by a factor of 1.8
[d] Subjects using firearms "sometimes or often". Most of these (12/15) reported that they always used hearing protectors when shooting
[e] At least one of parents or grandparents using hearing aid
* Significant result ($p < 0.05$)

Of the different noise sources, the highest odds ratios for self-reported hearing loss were associated with the use of waterjets, hydraulic wrenches/hammers and exposure to explosions (e.g. from oxy-arc burning), but none of these factors reached statistical significance alone. Few divers had experience working close to DP-vessel propellers or to seismic explosions, so the effect of these factors could not be calculated reliably.

Hearing thresholds are shown in table 2.

Table 2 Pure-tone hearing thresholds at a basic course for professional divers, and after 3 and 6 years.

		At course		After 3 years		After 6 years	
Ear	Frequency kHz	Mean	SD	Mean	SD	Mean	SD
Right	0.5	3.5	3.3	5.3	4.9	5.5	5.2
	1	5.1	4.0	5.8	4.4	6.6	3.8
	2	5.1	5.3	5.0	4.8	6.2	4.8
	3	6.0	7.8	6.3	7.6	8.2	8.8
	4	10.6	13.5	13.8	13.3	15.0	13.9
	6	15.1	14.4	15.9	15.4	17.4	15.9
Left	0.5	3.4	3.4	4.6	4.9	5.1	8.0
	1	5.3	3.2	4.2	4.3	5.8	6.8
	2	6.8	7.1	6.5	6.9	7.9	7.4
	3	7.9	8.0	9.0	8.5	9.4	10.1
	4	13.3	13.6	15.4	15.7	19.4	16.1
	6	19.8	18.8	18.8	19.2	21.1	20.3

* Pure tone audiometry, air-conduction thresholds in dB_{HL} not adjusted for age.

In both ears the greatest deterioration during follow-up occurred at 4 kHz. The multivariate analysis showed an age-adjusted threshold shift ($p < 0.05$) during follow-up, and the univariate analysis showed that this occurred only at 4 kHz (mean: 2.6 dB, 95% confidence interval: 0.9 – 4.3 dB).

The age-adjusted threshold shift was associated with occupational noise exposure (table 3).

Table 3 The effect of potential risk factors on hearing deterioration[a] at 4 kHz over a period of six years after completing a basic course for professional divers. Estimated difference (dB) in exposed vs. non-exposed subjects (t-test) or per unit of exposure (linear regression).

	dB		95% CI	
Noise exposure related to diving (divers confirming exposure to the following underwater noise sources)				
1. Waterjet	3.1		-0.6	6.8
2. Pneumatic rock drill	1.7		-2.2	5.5
3. Hydraulic rock drill	1.9		-2.1	5.9
4. Hydraulic wrenches/hammers	3.7		-0.2	7.5
5. Working close to DP-vessel propellers[b]				
6. Working close to seismic explosions[b]				
7. Exposure to other explosions (e.g. from oxy-arc burning)	5.6	*	0.1	11
Hearing deterioration per noise source (1-7)[c]	1.1	*	0.0	2.3
Noise exposure in general				
Have you ever experienced noise leading to tinnitus?	1.0		-3.2	5.2
Use of firearms (military or civilian)?[d]	-1.3		-5.3	2.6
Diving equipment (more than one alternative could be selected)				
Standard heavy helmet	2.7		-1.4	7.7
Light-weight helmet	-0.9		-4.7	2.9
Band mask	0.0		-4.3	4.2
Scuba gear	1.2		-3.0	5.4
Diving activity (per 100 dives)	0.3		-0.1	0.7
History of middle ear barotrauma	-0.2		-4.1	3.7
Tobacco smoking (past or present)	-0.3		-4.3	3.6
Alcohol consumption (weekly or more often)	-1.2		-4.8	2.5
Binge drinking (monthly or more often)	0.9		-2.6	4.5

[a] Thresholds for the right and left ear were averaged and age adjusted: adjusted threshold = observed threshold - expected threshold according to age and gender (ISO 7029).
[b] T-test not performed due to few positive answers.
[c] Adding one noise source, regardless of type, increased the threshold shift with 1.1 dB.
[d] Subjects using firearms "sometimes or often". Almost all of these (n=12) reported that they always used hearing protectors when shooting
* Significant result ($p < 0.05$)

The association seemed to be strongest with the use of waterjets, hydraulic wrenches/hammers and exposure to explosions, although only the latter reached statistical significance. Figure 1 shows the association between age-adjusted threshold shift and the number of noise risk factors ($\beta = 1.14$, $p < 0.05$).

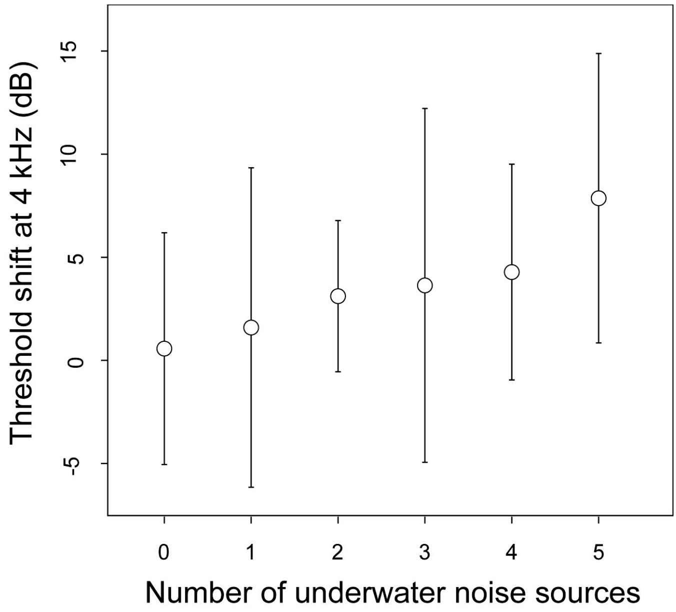

Fig. 1 The effect of occupational noise on hearing deterioration at 4 kHz over a period of six years after completing a basic course for professional divers. Thresholds for the right and left ear were averaged and age-adjusted: adjusted threshold = observed threshold - expected threshold according to age and gender (ISO 7029). Open circles and error bars represent mean values and standard deviation respectively. The divers were asked about exposure to seven different underwater sources that are known to produce potentially harmful noise levels (waterjets, pneumatic rock drills, hydraulic rock drills, hydraulic wrenches/hammers, DP-propellers, seismic explosions and other explosions e.g. from oxy-arc burning). The x-axis represents the number of specified underwater noise sources regardless of type.

The contribution from diving activity alone seemed to be small, i.e. only 0.3 dB (95% confidence interval -0.1 - 0.7 dB) per 100 performed dives. This was not significantly different from zero. Subjects who dived frequently also had a higher number of noise risk factors (Spearman's rho: 0.5, $p < 0.001$). Threshold shift was not associated with a history of middle ear barotrauma.

Discussion

Subjective hearing problems became more prevalent during follow-up, and there was a measurable age-adjusted threshold shift at 4 kHz. The findings were associated with occupational noise exposure. There was minimal, if any, contribution from diving *per se*. The hearing loss could not be explained by acute traumas.

The strengths of the study are the prospective design, the close follow-up and the extensive data collection on factors that may cause hearing loss. The divers were instructed to report any incidents of ear barotrauma causing hearing loss or tinnitus. They were young, newly trained and appeared motivated for the study. All divers were examined by two of the authors, who are otolaryngologists with experience in otoneurology and diving medicine. The threshold shift at 4 kHz was statistically robust since it remained significant in the multivariate analysis and after age-adjustment.

A larger study would be desirable for more precise risk estimates. Some of the subjects were lost to follow-up. They were all contacted by phone and encouraged to complete the study. Most of them reported that they felt that the follow-up was unnecessary because they were no longer diving professionally. There were no indications that these divers had experienced more problems at diving school. It is therefore unlikely that the results were affected by attrition bias.

A mean threshold shift of 2.6 dB is small, but not necessarily trivial. The shift was age-adjusted, which means that the actual measured hearing loss was greater. There was a considerable variability between the subjects, and greater losses occurred, particularly in the ones that were most exposed to noise. The follow-up period was six years and the divers were young. A longer diving career might lead to greater hearing loss later in life. Finally, the threshold shift at 4 kHz was accompanied by an increased prevalence of subjective hearing difficulties, which were also associated with noise exposure. The "audiometric notch" at 4 kHz is a recognized early sign of noise injury [14]. When an isolated progressive threshold shift occurs in this frequency in noise-exposed workers on land, noise is usually assumed to be the cause.

Occupational divers are sometimes subjected to extreme noise levels. In this study, the use of waterjets, hydraulic wrenches or hammers and exposure to explosions, such as may occur in gas pockets during oxy-arc burning, seemed to be associated with the greatest hearing effects. Peaks sound pressure levels up to 142 and 160 dB have been measured from waterjets and impact wrenches respectively [15]. Helmets and hoods offer limited and variable sound protection under water. In this study, the effect of different headgears was difficult to establish, although there was a trend for more hearing loss in divers who had experience using heavy helmets. This is in agreement with a previous study indicating more discomfort and higher temporary hearing threshold shift in a diver using heavy helmet than in divers wearing light helmet or band mask while operating different underwater tools [16].

Our study did not find evidence that diving per se causes hearing loss. The data does not exclude such an effect, but predicts that it should be smaller than the effect of noise. More severe hearing loss may be the result of acute inner ear injuries. However, no such injuries occurred in our population during follow-up, which included 27,232 dives. A large number of studies attest to the fact that some subpopulations of divers develop hearing loss [1-4, 8], while others do not [5, 6, 9-11]. Assuming an equal variation in individual susceptibility within each subpopulation, an explanation for the differences could be that hearing loss is in fact caused not by diving per se, but by other factors that differ between the subpopulations, such as exposure to noise and acute injuries.

Molvær and Albrektsen found progressive hearing loss in a six-year follow-up of noise exposed working divers [1]. Molvær and Gjestland measured noise levels inside different diving helmets during work with high-pressure waterjets and rock drills under water and found that this type of work produced temporary hearing threshold shifts [16]. Based on this and other studies [15, 17] it is assumed that noise plays an important role in the genesis of hearing loss among occupational divers.

However, other authors have found hearing loss in divers without significant noise exposure. Edmonds found a high prevalence of severe hearing loss among Australian abalone divers [4]. The divers with hearing loss usually attributed this to previous barotraumas, which is likely considering the severity of the measured hearing deficits. Other authors have found more moderate hearing loss. Haraguchi et al found progressive hearing loss in 18 Japanese fishery divers that were not exposed to excessive noise [2]. This was thought to be due to barotraumas, possibly unnoticed by the divers themselves.

The distinction between middle and inner ear barotrauma is not always clear. ‘Ear squeeze’ is the most common type of injury in divers. A study of 103 divers after a single dive found that 68% had otoscopic signs of middle ear barotrauma [18]. However, it is not known whether some of these traumas also conceal minor injuries to the inner ear. Some authors have suggested that repeated unnoticed barotraumas may be the cause of long-term hearing loss in divers [8]. This may be true, but our study did not find any difference in hearing between those divers who reported middle ear barotraumas and those who did not. This indicates that most cases of 'ear squeeze' really were middle ear barotraumas, without long-term consequences for hearing.

Decompression sickness may cause hearing loss, but more commonly leads to vestibular symptoms [19-21]. Two of the divers in this study reported transient symptoms after diving that could have represented DCS. Such symptoms should lead to immediate contact with a diving physician. The reason why the divers failed to do so could have been that the symptoms disappeared or that they interpreted their own symptoms as mild or insignificant. There were no indications of cochleovestibular injury in these cases, and the overall incidence of DCS in our study must be considered to be low with two possible cases in 27,232 dives. However, we cannot exclude the possibility that hearing loss might be more prominent in subpopulations of divers with a high exposure to DCS.

The differential diagnosis between inner ear barotrauma and inner ear decompression sickness is sometimes difficult since the cochleovestibular symptoms and signs may be similar. The distinction is nevertheless important, since the correct treatment for DCS is oxygen and recompression with as little delay as possible, while this treatment may worsen a barotraumatic injury. A barotrauma is in typical cases recognized by pain occurring during descent followed by hearing loss and characteristic otoscopic signs as described by Teed and others [22]. Inner ear DCS is typically characterized by vestibular symptoms and signs arising shortly after ascent from a dive that requires decompression stops according to standard diving tables.

No study has been able to demonstrate long-term hearing loss caused by diving per se in the absence of noise or acute injuries. Studies of guinea pigs [23] and minipigs [24] after repeated compression-decompression cycles have found severe hearing loss and histopathological changes in the cochlea suggestive of inner ear barotrauma. However, these animals may not be able to clear the ears the way human divers do. After myringotomy, guinea pigs seem to tolerate even extreme pressures without evidence of cochlear damage [25]. Duplessis et al measured hearing in humans before and after a repeated diving protocol and found no changes in pure tone audiometry thresholds [26]. There was a reduction in transient otoacoustic emissions but, as the authors acknowledged, otoacoustic emissions may be affected by small changes in middle ear function, for example due to edema, middle ear effusions or water droplets, and a change that occurs shortly after intensive diving is not necessarily of clinical consequence in the long term. Studies comparing experienced recreational scuba divers to non-divers have not found differences in hearing [9-11].

Tinnitus may accompany hearing loss in patients with inner ear disorders. The number of divers (n = 4) reporting chronic tinnitus ("often" or "always") remained constant during follow-up, and it was too low for statistical analysis of causative factors. However, many of them had experienced tinnitus temporarily after noise exposure. These divers had higher odds for reporting subjective hearing problems at follow-up and a higher hearing threshold shift at 4 kHz, but the difference did not reach statistical significance. The association between tinnitus, occupational noise and hearing loss is known from the literature [27].

In conclusion, occupational diving is associated with hearing loss. The main causes are noise and acute inner ear injuries. This study did not find an effect on hearing of diving per se. Until further research is available preventive efforts should focus on minimizing noise exposure and the risk of acute inner ear injuries due to barotrauma or decompression sickness.

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