Effects of freediving on middle ear and eustachian tube function

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Key words
Tympanometry; Repetitive diving; Ear barotrauma; ENT; Risk factors; Valsalva manoeuvre

Abstract
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Introduction: During descent in freediving there is exposure to rapidly increasing pressure. Inability to quickly equalise middle ear pressure may cause trauma to the ear. This study aimed to evaluate the occurrence of pressure-related damage to the middle ear and the Eustachian tube during freediving and to identify possible risk factors.
Methods: Sixteen free divers performed diving sessions in an indoor pool 20 metres' freshwater (mfw) deep. During each session, each diver performed four own free dives and up to four safety dives. Naso- and oto-endoscopy and Eustachian tube function tests were performed on the right and left ears before diving, between each session and after the last session. The otoscopic findings were classified according to the Teed classification (0 = normal tympanic membrane to 4 = perforation). Additionally, ENT-related complaints were assessed using a questionnaire.
Results: Participants performed 317 dives (on average 20 dives per diver, six per session). The average depth was 13.3 mfw. Pressure-related changes (Teed 1 and 2) were detected in 48 % of ears. Teed level increased significantly with an increasing number of completed sessions ($P < 0.0001$). Higher pressure-related damage (Teed 2) occurred in less experienced divers, was associated with significantly lower peak pressures in the middle ear and led to more ear-related symptoms. A preference for the Frenzel technique for middle ear pressure equalisation during freediving was shown.
Conclusions: Pressure exposure during freediving had a cumulative effect on the middle ear. Factors such as diving depth, diving experience and number of diving sessions correlated with the occurrence of higher Teed levels.

Introduction

Freediving is the oldest form of diving. In the past, free divers collected shells, sponges and pearls or went spear fishing. Several indigenous sea harvesting groups, like Japanese Ama divers, still practice freediving today.[1,2]

Freediving is also common among military and recreational divers. In the leisure sector, the main focus of freediving is on exploring the underwater world with minimal equipment. In competitive forms, longer apnoea times or distance and depth performance are targeted.

During descent in freediving, the body is exposed to rapid pressure increase over a short period of time. More than in any other sport, proper function of the Eustachian tube, the tympanic cavity and the mastoid, and use of an efficient equalisation technique are essential for prevention of middle and inner ear barotrauma.[3–11] Although learning the most appropriate pressure equalisation technique is an essential step in education of free divers, there is little or no research on pressure equalisation or pressure related changes in the middle ear. Besides the common techniques such as the Toynbee and Valsalva manoeuvres, there are less common mechanisms like the Frenzel and Delonca manoeuvres. Frenzel, which was developed in the German Air Force, is based on a pressure increase in the nasopharynx, created by compression of the tongue on the palate. The Delonca technique (also called 'hands-free' technique) is based on voluntary control of the tensor veli palatine muscle or moving the jaw to open the Eustachian tube. Another description of the procedure is to tense the muscles of the soft palate and the throat while pushing the lower jaw forward and down as if to start yawning. This should pull the Eustachian tube open.

The available literature on middle ear barotrauma includes mainly retrospective reviews or studies using subjective questionnaires.[5,6,9–11] Only a few studies have prospectively examined scuba divers for ear-related complaints and ear examination findings immediately before and after diving.[3,12–16] Several investigations have suggested that cases of ear barotrauma in commercial and recreational divers are likely under-reported.[9,10]

The aim of this study was to evaluate the occurrence of pressure-related damage to of the middle ear and the Eustachian tube during freediving and to identify possible risk factors.

Methods

The Ethics Committee of the University of Cologne, Germany, approved this observational prospective cohort study. The study (local register code 17-461) was registered in the German Register for Clinical Studies (DRKS: DRKS00013946). All participants signed a written consent before participation.

INCLUSION CRITERIA

Only divers with experience in freediving were included. None had been diving (freediving or scuba diving) for at least 24 hours prior to the study. Every participant presented a medical certificate confirming his or her physical fitness to dive.

DIVING SETTING AND ASSESSMENT

The study, including all examinations and dives, was carried out in one day.

Before diving, ear nose and throat (ENT) endoscopy and a Eustachian tube function test (ETFT) (tympanometry) were conducted. The endoscopy included the examination of the nasopharynx, the nose and both ears with a rigid 0 endoscope (Storz, Tuttlingen, Germany). Additionally, each participant filled in a questionnaire about their freediving experience (number of sessions, time period of freediving, maximum diving depth, last freediving session), preferred pressure equalisation technique and their diving complaints during past descents (ENT/non-ENT-related).

All dives were carried out in an indoor freshwater pool with a maximum depth of 20 metres' fresh water (mfw) (Dive4Life, Siegburg, Germany). Sixteen free divers participated in the study. The descending position (e.g., prone, head first), as well as the diving depth was not predetermined. Diving sessions were performed in groups of four.

The maximum number of dives per session per diver was set to four. Additionally, each diver could perform up to four safety dives for a group partner. The objective for the safety diver was to meet the free diver at a depth of 10 mfw and escort him to the surface.

For inclusion, each diver had to complete each full session and at least two sessions, but could drop out between any further sessions. In this setting, each diving session consisted of a minimum of four dives and maximum of eight dives (four regular + four safety dives). Participants recorded the depth of each dive directly after the ascent on a board, which was attached to a buoy in the pool.

Before the first session and at the end of each further session, divers were examined and interviewed on the surface. Examinations included endoscopic otoscopy, ETFT of both ears, and completion of a questionnaire.

OTOSCOPY

The endoscopic otoscopic findings were classified using the Teed scale for scoring barotrauma,[17] modified by Edmonds,[18] for the right and left ears separately. Teed level 0 defined a normal tympanic membrane, Teed 1 a retraction and increased vascularisation of the manubrium and shrapnel's membrane, Teed 2 retraction and hyperaemia of the entire tympanic membrane, Teed 3 fluid or blood in the middle ear, and Teed 4 a perforated tympanic membrane.

EUSTACHIAN TUBE FUNCTION TEST

ETFT was carried out using a Titan tympanometer according to the manufacturer's guidelines (Titan, Interacoustics A/S, Denmark) in sitting position for each ear separately. The frequency setting for tympanometry was 226 Hz. Baseline tympanometry was performed first (R-tymp), a second measurement was made after a Valsalva manoeuvre (V-tymp) and a third after swallowing (S-tymp). We refer to a previous publication for details.[16]

QUESTIONNAIRES

After each diving session, the following questions were asked:
1. Have you had problems with pressure equalisation or pain during the session? Options: yes or no.
2. Which pressure equalisation method was preferably used during the session? Options: Frenzel, Valsalva, Toynbee, Delonca. Multiple answers were allowed.

After completing all dives, all participants additionally rated the ease of the pressure equalisation during the sessions in response to the following question: "*Have you experienced changes in pressure equalisation during the training*? If yes, "*Did it get easier or worse during the training*?" and "*Have you skipped a dive because of equalisation problems*?"

STATISTICAL ANALYSIS

All data were anonymised. Findings for the right and the left ear were analysed separately. We used SPSS software, version 23.0.0.0 (IBM Corporation, USA) for statistical evaluation. Continuous variable data were presented as mean (SD) or median and 95% confidence intervals. Categorical variables are presented as absolute numbers and percentages. We applied the Kruskall-Wallis test for analysis of non-parametric continuous data and Pearson´s Chi-squared test for analysis of categorical data. A P-value < 0.05 was considered statistically significant. No corrections were made for multiple testing. All reported P-values are two-sided.

Results

DIVER CHARACTERISTICS

Sixteen free divers (five female) participated in the study. Their mean age was 51 y (range 27 to 67). The divers had a mean diving experience of 7 y (95% CI 4 to 9 y) with a mean number of 105 freediving sessions (95% CI 16 to 193) and a mean maximum depth of 28 metres (95% CI 20 to 36). The last dive was carried out on average two months (95% CI 1 to 3 months) before the study.

We defined three participants with ≥ 100 completed freediving sessions as experienced divers and two participants with ≤ 10 freediving sessions as inexperienced. The remaining 11 divers were defined as intermediate. Twelve participants (12/16; 75%) had confirmed ENT-specific problems in the past. Six participants reported problems with pressure equalisation before the study.

DIVES

During the study, 16 participants completed 317 dives; an average of 20 dives per participant. The mean number of dives per participant per session was six (95% CI 5 to 7 dives) with an average depth of 13.3 mfw (95% CI 9.9 to 16.8).

OTOSCOPIC FINDINGS

Initially, 28 ears (87.5%) were characterised as Teed 0 and 4 (12.5%) as Teed 1 (Table 1). Teed grading changed during the study to a higher level in 48% of the ears. Of these, Teed 1 was found in 40% and Teed 2 in 8% (Table 1). No ears received a Teed 3 or 4 score. Increased Teed score was associated with an increasing number of completed freediving sessions (P < 0.0001, chi-square test) (see Figure 1).

Correlation of otoscopic findings and diving experience

The experience of participants did not significantly influence the Teed level (P = 0.145, Chi-square test) though the study was underpowered to demonstrate this. Teed level 2 was evident only in less experienced divers (data not shown).

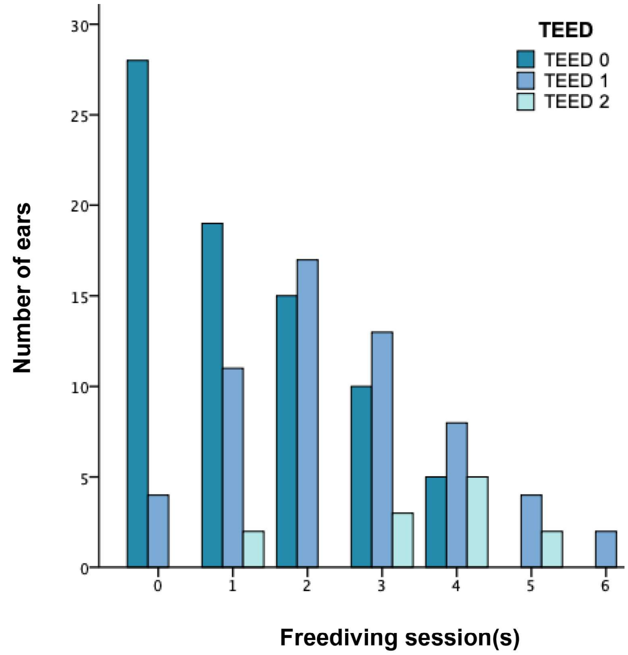
Correlation of otoscopic findings and diving depth

Participants with Teed 2 barotrauma performed significantly shallower dives than divers with Teed 1 or 0 (pair-wise comparison, Teed 2 vs. 1 P = 0.020, Teed 2 vs. 0 P = 0.025, respectively, Mann-Whitney U test) (Figure 2).

Table 1
Summary of all ear findings collected in the study according to the Teed classification. Two sessions were performed by all divers. After the second session, there were divers who did not perform any further sessions. Accordingly, the number of ear findings after session two decreased

Session	Number of ears			
	Teed 0	Teed 1	Teed 2	Sum
0	28	4	0	32
1	19	11	2	32
2	15	17	0	32
3	10	13	3	26
4	5	8	5	18
5	0	4	2	6
6	0	2	0	2

Figure 1
Change of otoscopic findings during the freediving sessions on both sides. The absolute number of findings with Teed 0, 1 and 2 scores is shown. The number of findings with Teed > 0 increases significantly with the consecutive number of sessions (P < 0.0001, Chi-square test)



Correlation of otoscopic findings and ETFT

Initially, all participants showed a type-A tympanogram in the ETFT. The peak pressure (R-tymp) in the middle ear remained stable during the consecutive sessions without significant changes in those divers with Teed score 0 and 1. However, participants with higher Teed level (Teed 2 vs. 0 and vs. 1), showed a significant negative shift of the peak pressure (P < 0.0001, Figure 3).

Figure 2
Average diving depth of all dives in participants with Teed 0, 1 and 2 scores. Participants with Teed 2 scores performed significantly shallower dives than divers with Teed 1 or 0 scores (pair-wise comparison, Teed 2 vs. 1 P = 0.020, Teed 2 vs. 0 P = 0.025 respectively, Mann-Whitney U test). The circles and asterisks represent outliers. mfw = metres' fresh water

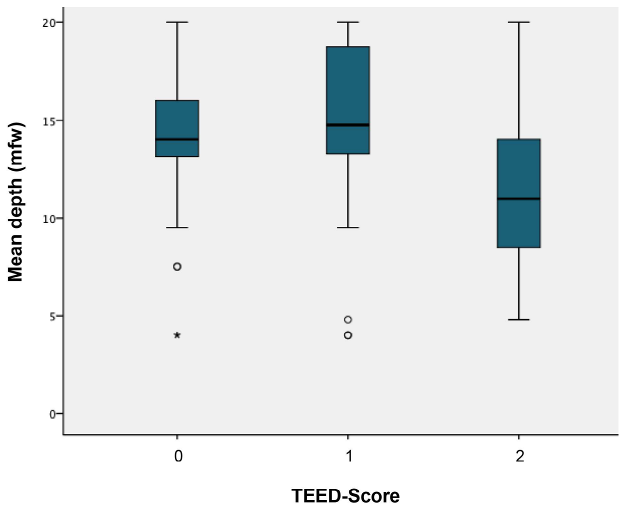
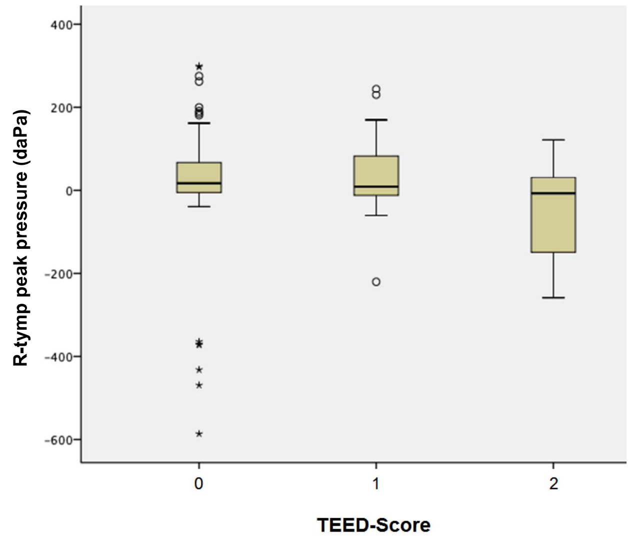


Figure 3
Correlation of the peak pressure (R-tymp, in deka Pascals [daPa]) and Teed score (Teed 0, 1 and 2). Participants with Teed 2 barotrauma showed a significantly lower peak pressure than those with Teed 0 and Teed 1, respectively (P < .0001). The circles and asterisks represent outliers



Correlation of otoscopic findings and equalisation technique

Most of the divers used more than one technique during the training. The techniques were the Frenzel manoeuvre in (56%), Valsalva (47%) and Toynbee (24%). Only 10% performed the Delonca technique during the diving sessions.

Participants with Teed 2 barotrauma more often employed the Valsalva manoeuvre than the Frenzel technique in comparison to divers with Teed 0 or 1 scores (P < 0.0001, chi-square test). Participants with high experience only used the Frenzel technique for pressure equalisation, whereas six of 11 intermediate divers and one of the two beginners applied the Frenzel manoeuvre (P < 0.002; chi-square test).

Correlation of otoscopic findings and pressure equalisation-related complaints

Divers with Teed 0 and Teed 1 scores did not report problems with pressure equalisation or pain during diving in 81% and 73% of cases respectively. Complaints of pressure equalisation were reported by 19%, 27% and 67% of divers with Teed 0, 1 and 2 scores respectively. Participants with Teed level 2 barotrauma reported significantly more complaints and pain during diving (P = 0.003, Chi-square test).

Regarding pressure equalisation, 6 of 16 (38%) participants affirmed that they had problems with equalisation during descent. Three of them reported that equalisation improved, two reported that it became worse. The one remaining diver reported no changes in equalisation. Three participants had to discontinue the dive because of the equalisation problems.

Discussion

Both scuba divers and free divers are exposed to pressure differences during diving. In scuba diving, a 'typical' dive lasts up to an hour, reaching the deepest depth relatively quickly and moving to a shallower depth toward the end of the dive. The special aspect of freediving is that the descent and ascent must take place within one breath. The depth of the dive is therefore, the dependent on the diver's apnoea time and the ability to easily equalise middle ear pressure. Thus, due to the nature of the sport, typical free divers make many more descents and ascents than scuba divers during a day of diving.

During the present study, 16 free divers were observed during training sessions and the pressure-related changes in the middle ear and the function of the Eustachian tube were evaluated in real time. The number of otoscopic findings with higher Teed scores increased significantly with an increasing number of completed diving sessions (Figure 1, Table 1). In 52% of the examined ears, no changes of Teed score were seen. In similar studies in scuba divers, the incidence of a Teed score > 0 was 58% and 74% after repetitive multiple-level dives in saltwater and freshwater respectively.[3,14] However, the scuba dives were carried out over several days and might be associated with a higher total pressure-related stress than the freediving sessions in the current study. Most otoscopic changes in freedivers were mild (Teed 1) and severe changes (such as Teed 3), were not present. This indicates that freedivers might cope with pressure exposure differently than scuba divers.

The experience of the participants might also influence the results. In the current study, most participants were intermediate in terms of freediving experience (number of sessions 11–99). Two were beginners with < 10 sessions and three divers reported ≥ 100 sessions. Teed 2 barotrauma was only present in divers with less than 100 sessions. Interestingly, several of them (6/16), independent of their level of experience, affirmed problems with pressure equalisation during previous diving.

Most of the participants used several techniques for pressure equalisation. The Frenzel technique was most preferred, followed by the Valsalva and Toynbee manoeuvres respectively. It is noticeable that experienced divers only used the Frenzel manoeuvre, while the less experienced also used other techniques. We may assume, that more experienced divers equalised differently (Frenzel) and more efficiently, thus showing less barotrauma. However, the mechanism of this manoeuvre should be further investigated under standardised conditions (i.e., in a pressure chamber). In further studies it should be investigated whether training in the correct execution of effective pressure equalisation mechanisms (e.g., the Frenzel manoeuvre) can lead to a reduction of barotrauma.

Our results further show, that shallower dives and use of Valsalva manoeuvre were associated with a higher incidence of Teed level 2 barotrauma and negative pressure in the middle ear (Figure 2). The association with shallow dives seems paradoxical at first, since these divers must have had a lower pressure load on the middle ear than divers with greater diving depths. But a similar association with the diving depths was shown during a study in freshwater scuba divers.[14] It should be remembered that as pressure increases, the greatest proportional changes in volume occur over the first 10 m of descent, thus this depth is clearly sufficient to cause changes in the middle ear. These findings suggest that beginners might be more susceptible to barotrauma than experienced free divers, who may transition through the first 10 m of descent more efficiently from an equalisation perspective. However, the small number of participants does not allow firm conclusions on the effect of divers' experience on pressure equalisation.

In relation to pressure change in the tympanic cavity, the R-tymp peak pressure did not change significantly after each diving session except in divers who developed Teed 2 barotrauma (see below). This contrasts with investigations in scuba divers which revealed a negative shift of peak pressure during repetitive dives; however these were carried out over several consecutive days.[15,16] A similar effect might also occur in freediving after diving over several consecutive days. Further studies are needed to evaluate this. The results of the current study show that the high-pressure load during freediving does not cause a significant change in Eustachian tube function – at least not more than in scuba diving.

In contrast to ears with Teed 0 and 1 scores, a significant negative shift of the middle ear pressure was present in ears with Teed level 2 barotrauma (Figure 3). Although higher Teed levels (Teed > 2) were not seen in the current group, Teed 2 was symptomatic in most of the divers. The more symptomatic pressure-related changes of the tympanic membrane and the middle ear correlated to previous publications in which scuba divers also revealed more symptoms in relation to higher Teed levels with the maximum of complaints (35%) if Teed 2 barotrauma occurred.[3,14] As this level of barotrauma is both relatively common and symptomatic in free divers and scuba divers,[3,14] this degree of pressure damage might be considered 'clinically relevant' barotrauma and should be communicated to the diver.

Altogether, participants reported ear-related complaints after 27% of the dives. This number is higher than in studies with scuba divers (19% in scuba divers in saltwater and 10% in freshwater).[3,14] This aspect is ultimately a logical consequence of the more rapidly changing pressure differentials in freediving and the consequent need for optimal Eustachian tube function.

The present study certainly has its limitations. The low number of participants limits generalisation and drawing of firm conclusions. In addition, only one day of freediving was analysed. Free divers should be examined over several consecutive days to assess the cumulative effect of pressure exposure. In addition, the divers were free to choose their diving profile and diving behaviour, so there was no standardised test set-up. The dives undertaken were sufficient to show some significant effects; however, the lack of standardisation reduced comparability. In addition, other factors not explored here might also play a role in Eustachian tube function. For example, neither the temperature of the water nor the chlorination were considered for this evaluation. Furthermore, the limitation of the ETFT has to be mentioned. The ETFT tympanometer offered the advantage of being easily operated and providing dynamic tympanometry during the pressure equalisation manoeuvres. However, no standardised values are available for this test.

Conclusions

In this prospective, observational cohort trial, repeated pressure exposure during freediving had a cumulative effect on the middle ear. Increasing number of diving sessions was associated with a higher number of pathologic Teed scores (Teed 1 and 2). Factors such as diving depth, diving experience and number of diving sessions correlated with the occurrence of higher Teed levels.

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